An Assessment of the Contribution of Micro-scale Activities to Personal Pollution Exposure in Commuting Micro-environments

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Abstract

Exposure to traffic pollution has become an increasing concern to public health. A number of studies have demonstrated that the air people breathe in while in transportation is particularly unsafe due to the high concentrations of carbon monoxide (CO), suspended particles (PM_{10}, $PM_{2.5}$ and PM_1) and ultrafine particles (UFPs). Some studies have suggested that peak exposures of approximately one hour- a typical time spent in a transport micro-environment- may have more damaging health effects than the 24- hour sampling times current standards apply to Despite the widespread interest in health effects from exposure to traffic pollutants, there is a distinct lack of research of this kind in New Zealand. The research presented in this thesis was designed to assess the effect of traffic emissions on personal exposure. More specifically, this project intended to examine how exposures differed on different modes of transport and also to investigate the extent to which transport micro-environments such as car parks, bus stops and metro stations contributed to personal exposure levels. This study is the first of its type in New Zealand, which simultaneously monitored CO, PM and UFP concentrations in the transport micro-environment. Vehicular traffic emissions were shown to be a significant source of air pollution in populated urban areas, especially in the transport micro-environment. This results of this study showed that the mode of transport is a significant determinant of personal exposure to pollutants. The information gathered indicated slightly different results for Christchurch and Auckland, possibly due to variations in back ground levels, traffic counts and meteorological conditions at the time of monitoring. Results from the research also showed that built transport micro-environments could experience extremely high levels of pollutant exposures. Although commuters spend a relatively short time in such environments, such short-term peak exposures could contribute significantly to adverse health effects. The results presented here have relevance for both public health and for policies aimed at reducing human exposures to traffic-related air pollution. It is imperative to incorporate policies which ensure that such built environments are as safe as possible in terms of keeping exposure levels at a minimum.

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CHAPTER ONE

Introduction

1.0 Introduction

Rapid modernisation and motorisation has led to urban transportation being a pressing concern in many mega-cities of the world (Qureshi and Lu, 2007). Emissions from the transport sector pose an increasing threat to climate change; it has been estimated that transport will contribute to 50% of the increase in carbon emissions in the next ten years (Colvile et al., 2003). Furthermore, motor vehicles are the major source of a number of pollutants which have the potential to affect the health of populations. Thus, urban air pollution has become a crucial problem due to growing urbanisation and increases in vehicle density (Romieu, 1999). Such critical global issues have resulted in a greater emphasis on the need for a sustainable transport system with a low impact on the global climate (Mobility 1030, World Business Council for Sustainable Development, 2004). New initiatives are being introduced to encourage people to use public transport, and cycling and walking have been promoted to reduce emissions from transportation. However, questions have been raised about health implications of doing this. According to a New Zealand study (Fisher et al., 2007), over 500 people over the age of 30 die prematurely, and 650,000 restricted activity days each year are attributed to traffic emissions. Because of a lack of exposure studies carried out in New Zealand, it is difficult to ascertain how individual choice of transport affects personal exposure. Furthermore, pollution level variations within journeys need to be investigated to gain a better understanding of circumstances that might lead to people being exposed to short-term peak levels of pollutants while commuting. It is vital to understand the factors that influence personal exposure in transport micro-environments to be able to "develop targeted control strategies in urban air quality management and to have a better understanding of health risks posed by air pollutants in different conditions" (Kaur and Niewwnhuijensen, 2009 p. 4737).

1.1 Conceptual Framework

1.1.1 Introduction

People spend a substantial amount of their outdoor time in the transport micro-environment (Schweizer, 2005). Exposure to pollutants in this micro-environment is often highly elevated compared to elsewhere, which results in individuals gaining a significant contribution to their daily exposure in a short period of time (Kaur et al., 2007). In such environments, exposure is not restricted to individuals in motor vehicles, it also includes people waiting around traffic congested streets, people working alongside busy streets, people in homes, flats, shops and other public places which overlook trafficked roads, people commuting on bicycles, and those waiting to use public transport. Motor vehicles emit a variety of air pollutants that are known to be associated with adverse health effects (Chertok et al., 2004). The most common pollutants include fine particles, carbon monoxide, nitrogen dioxide and volatile organic compounds (VOCs). In recent years, studies done in the United States, Europe and Asia have reported that human exposure to traffic-related air pollutants is associated with a range of health effects (Westerdahl et al., 2009). Studies carried out in Christchurch show an association between 24-hour concentrations of PM_{10} and mortality (1-day lag) and hospital admissions. A 10 $\mu g\ m^{-3}$ increase in 24-hour PM_{10} is associated with a 1% increase in all cause mortality and a 4% increase in respiratory mortality (Hales et al., 2000), and a 3% increase in respiratory hospital admissions of adults and children and a 1% increase in cardiac hospital admissions of adults (McGowan et al., 2000). The results of these studies are consistent with studies elsewhere in the world. However, in New Zealand, there is virtually no knowledge of the impact that travelling on different modes of transport has on the health of the commuters.

1.1.2 Short-Term Peak Exposures

Globally, many studies have been conducted to investigate the pollutant exposure in different modes of transport. However, exposure to traffic pollutants while undertaking different ‘micro- activities’ has not been studied as thoroughly. For example, Chau et al. (2002) recorded extremely high carbon monoxide (CO) levels in car parks, but did not investigate it further. In another experiment, Park et al. (2008) examined the effect of doors closing and opening inside trains. They found that PM_{10} and $PM_{2.5}$ concentrations monitored inside trains in underground stations when doors were open showed temporary increases. At the above ground stations, however, the opposite pattern became evident: the particulate concentration became lower when trains were opened because air that entered the train was less contaminated than the air already inside the trains. Park et al. (2008) also hypothesised that passengers moving around or taking a seat whenever the doors are open could result in the rise of particulate contamination. Additionally, Tsai (2008) asserted that bus commuters are potentially exposed to $PM_{2.5}$ and $PM_{1.0}$ emitted from vehicles passing by while they are waiting at roadside bus stops. Chan et al. (2002) reported that because buses run and stop more frequently than other vehicles, in-vehicle concentrations for PM_{10} were found to be higher when the doors were opened. They also concluded that PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ concentrations were elevated for motorcyclists when idled at traffic lights or stuck in traffic jams. Although they might only spend a fraction of their total journeys in these micro-environments, scientific evidence has demonstrated that there are very high levels of pollutants in these environments (Chau et al., 2000; Adams, 2001; Aarnio, 2005; Park et al., 2008; Tsai, 2008). Individuals, thus, gain a significant contribution of their daily exposure in a short period of time.

1.2 Rationale for Research

Several overseas studies have examined the exposure to traffic pollution on different modes of transport (Adams et al., 2001; Kaur et al., 2007; Kaur and Nieuwenhuijsen, 2009). The majority of studies done reveal that pedestrians and cyclists experience lower air pollution concentrations to those inside vehicles (Boogaard et al., 2009). Most of these studies have also found cars to be significantly more polluting than modes used for public transport, such as buses and trains (Chertok et al., 2004). However, there has been conflicting scientific evidence which show motor vehicles to have very low concentrations of carbon monoxide (Kaur et al., 2005; Mackay, 2004). Another study concluded that pedestrians are exposed to higher mean concentrations of pollutants than car drivers (Briggs et al., 2008). These conflicting findings suggest that local factors such as meteorological conditions, vehicle, driving and walking behaviors, monitoring methods and averaging periods could be the cause of such differences, therefore more research is required to “confirm the effects of exposures of changes in travel mode” (Briggs et al., 2008, p.13). Studies researching personal pollution exposure on different modes of transport have never been carried out in New Zealand. As has been demonstrated by studies carried out in the past, it is essential to consider local conditions unique to New Zealand which may influence personal exposure to traffic pollution. It would be scientifically unreliable to extrapolate results from other countries with different local conditions and differing climates when attempting to understand personal pollution exposure from traffic sources in New Zealand.

In addition to comparing exposures on different modes of transport, this study also aims to assess how exposure varies on a single journey; it seeks to identify short- term human exposure to peak concentrations of particulates, carbon monoxide and ultrafine particles (UFPs) in micro-environments such as sheltered car parks, bus stops and underground train stations. Although recent studies have established that exposure to such short-term peaks in pollution pose especial health threats, only a few studies have evaluated the relationship between personal pollutant exposure and micro-environments with high-level time resolution. Studies mostly utilise ambient pollutant measurements from fixed-monitoring sites as surrogates for exposure levels despite scientific studies reporting that such fixed sites significantly underestimate or have no association with the exposure of population sub groups (Chan and Wu, 1993; Fernandez- Bremauntz et al., 1993). Thus, it is clearly evident that direct personal exposure measurements are required in order to assess how traffic pollutants affect personal exposures in certain micro- environments.

This research will expand and complement the existing international knowledge base and provide the first data for New Zealand on personal exposure to traffic pollution.

1.3 Research Aims and Objectives

1.3.1 Research Aim

The major aim of this project is to assess the comparative risk associated with exposure to traffic pollution when travelling on different modes of transport, namely cycles, cars, buses and trains. More specifically, the purpose of this research is to calculate the contribution of micro-scale activities to personal pollution while commuting in cars, buses and trains. This includes time spent throughout the entire journey from door to door and includes activities such as walking through sheltered car parks, and waiting at bus stops and train stations.

1.3.2 Research Objectives

These aims can be broken into several distinct objectives which intend to answer these specific questions:

1. How does personal exposure to CO, PM_1, $PM_{2.5}$, PM_{10} and ultrafine particles (UFPs) from traffic emissions differ between use of cars, buses, on-road bicycles and off-road bicycles for transport in Christchurch city?

2. How does personal exposure to CO, PM_1, $PM_{2.5}$, PM_{10} and UFPs from traffic emissions differ between the use of cars, buses, bicycles and trains for transport in Auckland city?

3. Are there short-term peaks in pollution exposure on commuter journeys in cars, buses and trains?

4. What key events are responsible for such pollution ‘spikes’?

5. How and to what extent do confined spaces such as sheltered car parks, and bus and train stations affect a commuter’s daily exposure to air pollution?

6. How do meteorological factors such as wind speed and temperature affect a commuter's personal exposure to air pollution?

7. Does the time of day (morning or afternoon) affect a commuter's personal exposure to air pollution?

1.4 Thesis Structure

This chapter presents an overview of the purpose and objectives of this research. In addition, the rationale for conducting this research is discussed. Finally, the theoretical background and the conceptual framework to the study are introduced.

Chapter 2 will provide a comprehensive discussion of previous research carried out. It will start with a brief history of air pollution, and this will be followed by discussions of links between health and traffic pollution. Next, a brief summary of the five major pollutants central to this study will be introduced. Finally, a comprehensive literature review on personal exposure to traffic pollutants will be provided. This section will discuss inter-modal comparisons and how the mode of transport affects exposure. In addition, the literature on short-term peak exposures in transport micro-environments will also be summarised.

Chapter 3 will introduce the study areas and the regional settings. It will start with a brief overview of air pollution in New Zealand as a background context and reference point for this study. This will be followed by an investigation of New Zealand's air quality guidelines and standards and an examination of their effectiveness in reducing pollution levels. The two study areas, Christchurch and Auckland will be presented as two separate case studies, each with a discussion of air quality and use of public transport and how these factors might affect personal exposure on commuters in the two cities.

Chapter 4 is dedicated to the methods used in this research project. The chapter will include a brief description of the equipment and tools utilised to meet the thesis goals and objectives. It will include a section on the study vehicles used, and the pre-fieldwork preparation that had to be done before the fieldwork commenced. The sampling area and design will also be discussed in this section. Finally, a short note on the data analysis will be presented.

The following two chapters will present the results. Chapter 5 will be dedicated to Christchurch, and Chapter 6 to Auckland. For each, the inter-modal results will be presented first. This will be followed by the results for the micro-environments in the journeys. This included a sheltered car park and indoor and outdoor bus stops in Christchurch. In Auckland the micro-environments consisted of an underground car-park, outdoor bus stop, an outdoor train station and Britomart, the underground metro station. The results for other factors (meteorological influences and the effect of time of day on pollution exposures) will also be presented.

Chapter 7 will consist of a discussion and interpretation of the results. An extensive examination of the transport micro-environment will be included to assess if commuters are exposed to short-term peaks of pollutants while travelling on journeys. This is especially important as it provides insight into human activities that exacerbate personal exposure. Finally, the limitations of the methodological approaches used will be outlined.

Chapter 8 will present the overall conclusion of the study, along with the policy implications of the study. Additionally, areas for further research will also be identified. The references and appendix will follow this chapter.

1.5 Summary

Chapter 1 provides an introduction to the thesis topic. It outlines the increasing problem of urbanisation, which results in an exponentially growing number of vehicles on the road in cities worldwide. Since exposure to pollutants in the transport micro-environment is often more highly elevated compared to elsewhere, individuals gain a significant contribution to their daily exposure in a short period of time. This has significant implications for the health of commuters. Transport research which investigates personal exposure on different modes of transport and at different times on a journey has never been carried out in New Zealand. The research will complement the existing knowledge base and will assist in providing information about hazardous micro- activities that lead to peaks in pollutant exposures. Furthermore, the research will also help transport decision-making at personal and societal levels.

CHAPTER TWO

A Review of Past Literature and Research

2.0 Introduction

McGranahan and Murray (2003, p.2) define air pollution as ‘the presence of substances in air at concentrations, durations and frequencies that adversely affect human health, human welfare [and/] or the environment’. Increases in both global population and energy consumption have led to air pollution being rapidly recognised as a major environmental and public health issue in both developing and developed nations (World Health Organisation, 2005). There has been considerable progress in the epidemiology of air pollution in recent decades, with significant consequential changes in international air pollution guidelines and more systematic approaches for formulation of air pollution guidelines. Although most of these advances have originated in more affluent regions, important developments have taken place in many other parts of the world (McGranahan and Murray, 2003). Research consistently indicates that adverse effects of outdoor air pollution stem from transport as an important contributor to these effects. A multitude of air contaminants of varying toxicity originate from road transport, such as carbon monoxide, nitrogen oxides, benzene and particulate matter. This chapter will review the epidemiological evidence on the effects of transport- related air pollution. The aim of this chapter is also to synthesise relevant knowledge on the comparative risk associated with exposure to traffic pollution when travelling on different transport modes, namely cycles, cars, buses and trains. More specifically, the contribution of micro-scale activities to personal pollution exposure while commuting in cars, trains and buses will also be reviewed. In addition, a brief history of the origin of air pollution will also be discussed.

2.1 Air Pollution in its Historical Context

Air pollution is not a recent phenomenon. The use of wood for cooking and heating was the earliest known precursor of anthropogenic air pollution (McGranahan and Murray, 2003). Historical evidence from early humans demonstrates that they were exposed to the detrimental effects of smoke in their dwellings (Brimblecombe, 1987). This link between unhealthy air and disease was established by the discovery of mummified lung tissues of ancient humans: the blackening of lung tissues through exposure to particulate air pollution in smokey environments appeared to have been common in early civilizations (Brimblecombe, 1987). However, by the beginning of the thirteenth century, dwindling supplies and rising costs of wood resulted in the widespread use of coal as the primary source of fuel (Kessel, 2006). The use of coal did not abate in the eighteenth century, when industrialisation and urbanisation led to further degradation of the quality of air (Kessel, 2006). It was only then that the local impacts of air pollution on human health and the environment began to be documented systematically; it was in the eighteenth and the nineteenth centuries that statistics were collected on deaths resulting from air pollution around the world (McGranahan and Murray, 2003; Elsom, 1992). Europe and North America saw consistently rising air pollution at the turn of the twentieth century, and in December 1952, an episode of stagnant atmosphere of smog and sulphur dioxide led to about 4000 excess deaths in London (Brimblecombe, 1987). It was around this time that the changing attitudes and policies towards air pollution and its effects on health began to surface. As public concern about the dangers of air pollution grew, more effective international action was implemented. The World Health Organisation (WHO) introduced guidelines on ambient air quality and stringent policies for reducing emissions of toxic pollutants were put in place (WHO, 2000).

2.2 Air Pollution and Health

The importance of air in early societies can be seen first in the medical systems of ancient cultures. For example, that air had a formative place in early Egyptian medical thought can be seen in their belief that ‘life lay in breath’ (Porter, 1999). In his book *Air, the Environment and the Public Health,* Kessel (2006, p. 24) states that perhaps one of the earliest concepts of air as the natural environment and its effects on health originated as early as 430 BC in Greece as the following passage from the *Hippocratic Corpus* (circa. 430 BC) states:

> "*When an epidemic of one particular disease is established, it is evident that is not the regimen but the air breathed which is responsible. Plainly, the air must be harmful because of some morbid secretion which it contains*."

Recent epidemiological and toxicological evidence on air pollution and health strongly corroborates the early link between air pollution and health. A review of this evidence reveals that increasing urban air pollution represents a serious threat to human health worldwide (Schwela and Zali, 1999). Research in recent decades consistently indicates that transport is an important contributor to outdoor air pollution that harms health (Dora and Phillips, 2005). It is well established and widely accepted that air pollution from transport sources has an adverse effects on numerous health outcomes including mortality, morbidity and hospital admissions (Kingham et al., 2007). Not only does transport related air pollution increase the risk of death from cardiopulmonary causes, it also increases the risk of respiratory symptoms and diseases that are not related to allergies (WHO, 2005). In recent years, studies done in the United States, Europe and Asia have reported that human exposure to traffic-related air pollutants are associated with a range of health effects (Westerdahl et al., 2009). For example, Brauer et al. (2002) and Garshik et al. (2003) report on the respiratory ill effects of such exposure. Additionally, adverse effects on children's lung developments (Gauderman et al., 2007), and increased risk of cardiopulmonary and stroke mortality related to close proximity of traffic (Hoek et al., 2002) have also been reported.

2.3 The Pollutants

2.3.1 Introduction

Several major classes of air pollutants of varying toxicity originate from road transport. These contaminants emerge from the tailpipes of vehicles with internal combustion engines, from other vehicle components (such as brake and clutch linings, tyres and fuel tanks) and from road surface wear and treatment materials (WHO, 2005). Vehicle emissions can be labelled as one of the most important source for some pollutants of great concern such as carbon monoxide, nitrogen dioxide, volatile organic compounds

(VOCs) and particulate matter. Before delving further into the nature of these contaminants, it is important to understand that the composition of motor vehicle exhaust depends on the fuel used as well as on the type and operating condition of the engine (Romieu, 1999). Generally, the major differences between diesel and petrol engines are in the quantity of carbon monoxide, particulate and nitrogen dioxide produced (Chow and Chan, 2002). While the major concerns of diesel engine emission are nitrogen dioxide, particulate matter and sulphur dioxide, petrol engines emissions are known to have much higher levels of carbon monoxide (Chan et al., 1999). As Wohrnschimmel et al. (2008) contend, the air people breathe while in transportation is particularly unsafe due to the high concentrations of carbon monoxide (CO), suspended particles (PM_{10} and $PM_{2.5}$) and volatile organic compounds. Furthermore, with respect to CO, transport microenvironments have been identified as the most polluted spaces in comparison with other microenvironments (Georgoulis et al., 2002). With regard to VOCs, transport microenvironments were also shown to be a significant contributor to personal exposure (Edwards et al., 2006). A study conducted by Behrentz (2005) showed that such microenvironments are responsible for 15% of total $PM_{2.5}$ personal exposure. For every hour that was spent in transport, commuters are exposed to higher than average levels of air pollution. This has been shown for a wide variety of cars, buses, subways and cycles.

As the scientific literature demonstrates, there are a considerable number of pollutants resulting from vehicular emissions. They include many types of particulates, sulphur oxides, carbon monoxide, lead, nitrogen dioxide and a variety of VOCs (Murray and McGranahan, 2003). A thorough examination of all the pollutants is required to better understand the impacts that vehicular emissions have on human exposure and health. However, due to time and research constraints, only five categories of traffic air pollutants will be discussed. The five pollutants central to this thesis include carbon monoxide, PM_{10}, $PM_{2.5}$, PM_1 and ultra fine particles (UFPs).

2.3.2 Carbon Monoxide (CO)

Carbon monoxide (CO) is a gas produced by the incomplete combustion of carbon-based fuels, and by some industrial and natural processes. The most important outdoor source of CO can be attributed to emissions from petrol-powered vehicles. Although it is always present in the ambient air of cities, maximum concentrations are often common in major highways during peak traffic conditions. Poor ventilation near unvented combustion appliances can lead to very high CO levels indoors (Murray and McGranahan, 2003). Short or long-term exposure to CO can lead to severe health complications (Romieu, 1999). CO is rapidly absorbed in the lungs and is taken up the blood, greatly reducing the oxygen carrying capacity of blood. Organs which are dependent on a large oxygen supply are the most at risk, particularly the heart, the central nervous system and foetus. Research has also confirmed that subjects with previous cardiovascular disease seem to be the group most sensitive to CO exposure.

The first air pollutant to be studied in vehicles, CO continues to be used as a marker of exhaust emissions (Wiesel, 2001). When studying the personal exposure to carbon monoxide, declining CO emissions over time have to be taken into consideration, especially in North America and Western Europe (Kaur et al., 2007). While in the 1970s CO levels were tens of ppm, in the 1990, this decreased to a few ppms. Duci et al. (2003) examined CO levels experienced by pedestrians along heavy traffic routes in the urban areas of Athens, and mean exposure concentrations were found to be similar in winter and summer-11.5 and 10.1 ppm respectively. The study identified the mode of transport commuters choose to travel in as one of the main factors that had a significant influence on CO concentrations. In another study conducted along Champs Elysees Avenue in Paris, France measured the average CO exposure concentration for pedestrians to be 5ppm (Dor et al., 1995). Even lower pedestrian exposures have been recorded in the studies undertaken in the United Kingdom (UK) with little variation in exposure levels experienced across the country. A study carried out by Kaur et al. (2005) found the mean personal exposure concentration to be 0.9 ppm. The same study reported no difference in CO personal exposure levels based upon the timing, position on pavement and walking direction of the travel. As has been established already, the mode of transport can influence the exposure experienced (Kaur et al., 2007). With regards to CO exposure, it has been generally noted that pedestrians and cyclists often experience exposure concentrations that are lower than those experienced within vehicles (See Boogaard et al., 2009).

2.3.3 Particulate Matter (PM_{1}, $PM_{2.5}$, PM_{10})

Particulate matter (PM) is a complex mixture typically divided in fractions based on particle size. Coarse particles with diameters less than 10 microns correspond to particles defined as PM_{10}. Fine particles, on the other hand, with diameters less than 2.5 microns are collectively referred to as $PM_{2.5}$ (Tsai et al., 2008). These particulate matters can be attributed to two major sources. While the first is a natural aerosolisation of crustal matter, which includes re-suspended dust from roadways, sea salt, and biological material such as pollen and fungi, the second source is combustion of fossil fuels (Koenig, 2000). Exposure to airborne particulate matter has become a serious public health issue (Cheung et al., 2008). Both PM_{10} and $PM_{2.5}$ are known as major traffic- related air pollutants in urban environments and recent epidemiological studies have demonstrated that exposure to airborne PM is responsible for a wide range of adverse health effects (Pope et al., 2002). A study done in 2002 (Pope et al.) discovered that a 10 μg^3 increase in fine particulate pollution was associated with approximately a 4%, 6% and 8% increased risk of all cause, cardiopulmonary and lung cancer mortality respectively. Several studies indicate the $PM_{2.5}$ particulates are more directly linked to negative health effects than are PM_{10} particulates, as the smaller particles can penetrate further into the lungs than PM_{10} particulates and can reach the alveoli of the lungs (Ministry for the Environment, 2007). ‘There is an abundance of mass concentration, distribution, and chemical component measurements for ambient $PM_{2.5}$ and PM_{10} in many urban and industrialised areas. However, much less is known, and even less done about PM_{1} (Lin and Lee, 2004; p. 469). These fine particles in urban areas originate primarily from the gas-to-particle conversion processes within the atmosphere. Secondary anthropogenic combustion products from vehicular traffic and energy production are also known sources of PM_{1} (Hildemann et al., 1991; Schauer et al., 1996). The mass of the sub-micronic fraction is mainly composed of anthropogenic components such as heavy metals, organics and sulphates, thus enhancing PM_{1} toxicity (Vecchi et al., 2004).

2.3.4 Ultrafine Particles

Among the numerous components of vehicle-produced pollution, ultrafine particles (UFPs) have generated considerable interest in recent years (Tsai et al., 2008; Morawska et al., 2008; Hagler et al., 2009; Berghmans et al., 2008). Defined as those particles with diameters smaller than 0.1 um, ultrafine particles are abundant in number but contribute little to the mass (Penttinen et al., 2000). The effect of ultrafine particles on adverse health effects is clearly established in scientific literature; studies have shown that ultrafine particles are more toxic than larger particles (Wahlin et al., 2001). Given their small size, UFPs have been shown to efficiently penetrate the respiratory system and even affect extrapulmonary organs (Elder et al., 2006). UFP exposure is also detrimental to respiratory and cardiovascular health (McCreanor et al., 2007).

In urban areas, ultrafine particles are primarily sourced from emissions from motor vehicles, and most UFP emissions can be attributed to diesel vehicles (Fine et al., 2004; Int Panis et al., 2006). Investigations on human exposure to UFPs have discovered that different modes of transport resulted in different exposures (Kaur et al., 2006). Considerable variability was seen in UF particle exposure within a few seconds and over a few meters as commuters moved through polluted microenvironments (Morawaska et al., 2008). For example, a study carried out by Gourioi et al. (2004) showed that car passengers are exposed to high peaks of up to 10^6 particles cm^3. As these results indicate, it is important to realise that the influence of time-activity and movement can be easily missed by using averaged results, leading to underestimation of exposures (Morawaska et al., 2008).

2.4 Comparison to Inter-modal Exposure to Pollutants

2.4.1 Introduction

Various studies have been carried out to analyse the exposures to air pollution by comparing different modes of transport. One such study (Tsai et al., 2008) reported that previous studies on commuters' exposures to VOCs have shown significant differences between commuters using motorcycles, cars or buses as commuting modes in Taipei.

Similarly, another study states that a common result for gaseous air pollutants and elemental carbon was that private and low- capacity public transport vehicles are among the microenvironments with the highest commuters' exposures, whereas lower levels of such pollutants have been found in high capacity transport vehicles like buses and metro (Adams et al., 2002). In comparison to studies investigating exposure to gaseous pollutants, there have been far fewer exposure studies examining fine particulate matter in transport microenvironments. This could be attributed to the financial constraints and practical matters such as the lack of availability of appropriate personal monitoring equipment with suitable detection limits (Kaur et al., 2007). However, as Kaur et al. (2007) further indicate, the numbers of studies examining personal exposure concentrations in transport microenvironment have increased over the last decade for fine particulate mass and more recently ultrafine particles. Investigations in a number of cities around the world have shown that exposure to air pollutants for commuters in motor vehicles is considerably higher than ambient urban concentrations, and higher than concentrations found in other urban transport modes such as trains, buses, cycling and walking (Batterman et al., 2002; Torre et al., 2000).

2.4.2 Pedestrian Exposure

As pedestrians move around through a network of streets in an urban environment, they are inadvertently exposed to vehicle pollutants by vehicle emissions released by traffic and/or influenced by dispersion conditions (Kaur et al., 2005). Although there have been many studies investigating personal exposure across different vehicular modes of transport, studies examining pedestrian personal exposure to fine particulate matter, and carbon monoxide are rare. Kaur et al. (2005) carried out a study in central London along a busy dual carriageway. The study looked at pedestrian exposure to $PM_{2.5}$, UFPs and CO. The results for the different pollutants show a variation in exposure at different timings, pavement positions and sides of carriageway. Additionally, fixed monitoring stations were shown to underestimate the particulate and carbon monoxide exposure that pedestrians experienced. This particular study reported the average $PM_{2.5}$ exposure to be 37.7 μg^3 with the exposure being significantly lower in the morning than the afternoon.

The average CO exposure was 1.3 ppm and varied between 0.1 and 3.8 ppm. In another experiment done in 2004 in Northampton, UK (Gulliver and Briggs) showed the average pedestrian exposure to particulate matter ($PM_{2.5}$) to be much lower at 15.06 μg^3. The mean exposure to PM_{10} was found to be 38.18 μg^3. The same study compared pedestrian exposure to concentration for in-car journeys and reported that exposures to PM_{10} in cars is 16% higher than for journeys made by walking. Compared to fixed monitoring sites, concentrations for both walking and in-car journeys are higher by 30% and 67% respectively. In another study carried out in Copenhagen, average dust exposure was found to be 1.7 time higher for car users than for pedestrians. More recent studies, however, describe results which are markedly different. Briggs et al. (2008) found that mean exposures while walking are greatly in excess of those while driving, by a factor of 4.7 for PM_{10} and $PM_{2.5}$, and by 2.2 for fine particle mass. This could largely be attributed to the in-car filtration system which insulates the car against air pollution present in the street.

2.4.3 Personal Exposure on Cycles

In many cities, cycling is promoted as a healthy transport alternative of transport that reduces traffic congestion, along with increasing human physical activity (Thal et al., 2008). However, the exposure of cyclists to atmospheric pollutants as they pass through a variety of micro-environments has not been as thoroughly investigated. An early study carried out by Harlos and Splenger (1989) stated that people who use bicycles as a mode of transport for getting to and from work have a high potential for exposure to vehicular pollution. Another study done two years later (Bevan et al., 1991) makes the same conclusion: commuting by bicycle during peak traffic periods may lead to significantly increased levels of exposure to CO, volatile organic compounds and respirable suspended particles due to motor vehicles exhaust fumes. When comparing pollutant exposure in different modes of transport, a number of investigations around the world have shown that exposure to air pollutants for commuters in motor vehicles is higher than concentrations found in other modes of transport such as walking and cycling (Chertok et al., 2004). Similarly, a Dutch study sampled CO, nitrous dioxide (NO_2), benzene, toluene, ethylbenzene and xylenes (BTEX) on people either driving a car or riding a bicycle (van Wijnen et al., 1995), and found that measurements showed that the exposure levels were greater for the car drivers than for the cyclists. The same study showed that even though the respiratory average for cyclists are 2.3 times higher than car drivers, those who drive cars still received twice as much benzene exposure as those who used bicycles as a mode of transport. Although it could be argued that due to higher speed, car drivers are exposed to a lesser degree, Rank et al., (2001) found that at rush hour the speed of cars almost match the speed of the cyclists. Also, they further assert that because children are passive passengers who exhale the same amount of air in both situations, children transported on the back of a bicycle inhale a lower concentration of pollutants than they would inside a car.

A host of studies have demonstrated that a cyclist's personal exposure levels to particulate matter is significantly lower than those traveling in cars or buses (Gee and Raper, 1999; Rank et al., 2001; Adams et al, 2001). A study measuring $PM_{2.5}$ personal exposure levels in transport microenvironments in the UK (Adams et al., 2000) found mean exposure levels to be fairly similar in bicycle, bus and car modes. However, the the subjects on cycles were shown to have slightly lower exposure to fine particulate matter. One explanation for such lower exposure rates for bicycle users could be that they are exposed to lower levels of $PM_{2.5}$ because they are typically on the outside edge of the road or because of the ability of cyclists to avoid traffic jams. In addition, as Gee and Raper (1999) contend, cyclists travel beside traffic rather than behind, thus reducing the direct exposure to vehicle exhaust emissions. When considering the exposure to CO levels, several studies have shown that CO exposures for cyclists are slightly higher than for pedestrians (Kaur et al., 2005; Mackay, 2004). The mean concentration for CO exposure fell between 1.3 and 2.7 ppm for cyclists along an inner city route around Amsterdam in Netherlands (van Wijnen et al., 1995). In another study, Bevan et al., (1991) recorded CO exposure concentrations between 5.3 and 17.9 ppm for cyclists commuting in and around Southampton.

A comparison of air pollution exposure for five commuting modes in Sydney (Chertok et al., 2004) showed that walking and cycling commuters have significantly lower levels of benzene exposure (5.7 and 6.17 ppm respectively) compared with car commuters whose exposures averaged 12.29 ppm. Also, the cyclists in the study had significantly lower levels of NO_2 (24.58 ppb) than those who travelled by car (29.70 ppb), bus (44.30 ppb) and also those who walked (26.08 ppb). It is, however, important to realise that these results could have been strongly influenced by the study location being close to the Sydney CBD where ambient NO_2 levels are much higher than the rest of the city (Chertok et al., 2004).

2.4.4 Personal Exposure in Cars

In the majority of the world the number of cars is increasing exponentially. This is coupled with an increase in concern about the impact on human health caused by traffic emissions (Rank et al., 2001). As has been substantiated from the evidence provided by previous research, exposure to pollutants from traffic related emissions affects different types of road users in different ways and to differing degrees. Car drivers and passengers spend a substantial amount of time inside automobiles, and it is essential to understand the effects of exposure to pollutants in-vehicle. Wiesel et al., (1992) states that research has discovered inside-car concentrations for volatile organic compounds to be up to fifty times higher than the outdoor concentrations. Van Wijnen and Van der Zee (1998) reported in-vehicle concentration for benzene in three American cities to be higher than ambient air concentrations (10- 17 μg^3). This is very significant because benzene, considered the most hazardous of the BTEX compounds, is a known carcinogenic and has serious health implications (WHO, 1993). Another study done in Sweden (Gennart et al., 1994) reiterated these findings: in-vehicle benzene concentrations were significantly higher than the ambient outdoor concentration. The in-vehicle benzene concentration peaked at 100- 200 μg^3 when driving in dense traffic, and when waiting in queues, the figure rose to 200- 400 μg^3. A later study conducted in Korea (Jo and Choi, 1996) investigating the occupants' exposure to aromatic volatile compounds while commuting on an urban-suburban route found that VOC concentrations were lower in buses when compared to cars. Concentrations in cars were also higher than those found in a subway train (Fromme et al., 1997/98). A Danish study (Rank et al., 2001) concluded that car drivers experienced 3-4 times higher BTEX concentrations and two times higher exposure of particulates than cyclists. Chertok et al. (2004) found that car commuters received the highest exposure to BTEX concentrations than any of the other commuting modes. Factors such as the benzene concentration in gasoline (Rank et al., 2001) and the age of cars influence the in-vehicle concentration levels for VOCs. For example, a study carried out in Sydney, Australia showed in-car concentrations for pre- 1986 cars without catalyst equipment to be twice as high as newer cars (Duffy and Nelson, 1997).

Amongst all the modes of transport, in-vehicle exposure levels have been the most thoroughly studied for $PM_{2.5}$ (Kaur et al., 2007). Two studies done in London (Adams et al., 2001; Kaur et al., 2005) both obtained similar average exposure concentrations in the summer (37.7 μg^3) and during winter (33.7 μg^3). Both studies also found that passengers travelling in private vehicles experienced higher concentration levels in comparison to other transport modes. Significantly higher rates of particulate matters were found in a study was conducted in Guangzhou, China where the in- vehicle measurements of particulates and carbon monoxide in four major transportation modes along typical urban routes were examined (Chan et al., 2002). The $PM_{2.5}$ and PM_{10} ratios in all measured transportation modes were high (76-83%). For taxis, the PM_{10} was measured at at 116 μg^3, while the $PM_{2.5}$ was 90 μg^3. While in comparison, A/C buses and non-A/C buses both fared worse than the taxis, with a higher exposure level to both particulate matters. These results are proportionately consistent in other studies done in Hong Kong, London and Munich, with the particulate exposure in taxis being less than those experienced in buses, especially if they are air-conditioned. Also, in all the studies, subways were found to have the least amount of exposure to particulate matter (Chan et al., 2002; Adams et al., 2001; Praml and Schierl, 1999). In metropolitan cities, vehicle exhaust, especially those diesel fuelled, is a major source of particulate matter, and the in-vehicle air quality is often deteriorated by the influence of neighbouring vehicle exhaust emissions(Chan et al, 2002). The substantially higher in-vehicle exposure levels to both PM_{10} and $PM_{2.5}$ can be attributed to loose vehicle emissions standards, poor vehicle maintenance and the slow moving patterns in Guangzhou, consequently resulting in increase of emission source strength and the decrease in distance between vehicles. The ventilation condition of the transport also played a major role in determining the in-vehicle particulate pollution, with the conditioning system possibly filtering part of the larger portion of PM_{10}. This results in $PM_{2.5}$ level being relatively higher in air-conditioned vehicles (Chan et al., 2002).

When examining in-vehicle CO exposure concentrations, some conflicting evidence surfaces. Low levels of CO exposure concentrations were observed for cars in London (Kaur et al., 2005a) and in Leeds (Mackay, 2004), with the maximum level being below 3.5 ppm for both studies. Another study carried out earlier in London (Dickens, 2000) recorded higher concentration levels with the maximum of 14.1 ppm in London. Car conditions such as the inclusion of ventilation, rather than traffic density, has been attributed to such exposure differences. Quite contrary to these findings, Chan et al. (2002) found that in the city of Ghuagzhou, China the highest average for CO exposure concentrations were found in air conditioned taxis at 28.7ppm. This figure was found to be lower for non air-conditioned taxis (18.7 ppm), air-conditioned buses (8.9 ppm) and non air-conditioned buses (8.2ppm). Chan et al. (2002) reason that because it is common practice for drivers to close the fresh air vent when using the air-conditioning, the low exchange rate combined with the presence of internal sources enhances the accumulation of CO level in an air-conditioned taxi (Chan et al., 2002). Alternatively, in a non-air conditioned taxi, the roadway air with much lower CO concentrations helps dilute the in-taxi air with higher CO concentrations. Focusing on other studies which examine CO concentrations in cars, a study conducted in Taipei, Taiwan Liu et al. (1994) found the CO exposure concentration in a private car to be 11.0 ppm. Another experiment carried out in Athens, Greece found the average CO concentration to be 21.4 ppm (Duci et al., 2003). Alm et al. (1999) recorded a diurnal variation with lower exposure concentrations in the car during the mornings and afternoons.

The study done by Chortek et al. (2004) comparing the air pollution exposure for five different modes in Sydney corroborates the findings from other cities that BTEX concentrations in cars are higher than in other transport modes. The Household travel survey data set 2001 carried out by the Transport Data Centre (2003) estimated that benzene exposure over a 40 year period of commuting would result in a motorist inhaling 411 mg of benzene compared with 126 mg for a train commuter. One reason for comparatively higher rates of benzene exposure in cars could be explained by the fact that the main source of air intake for a car is from the highly contaminated exhaust of all the vehicles on the road. Car commuters fare better than those who commute by bus in terms of their exposure to NO_2 (Chertok et al., 2004). Bus commuters recorded the highest average exposure to NO_2 at 44.30 ppb. In comparison, car commuters are exposed to mean concentrations of 29.70 ppb. However, those in cars still suffer a disadvantage when compared to those travelling through other modes of transport. While train commuters faced the lowest exposure of NO_2 at 14.85 ppb, cyclists ranked safer than pedestrians when considering exposure to NO_2, the concentrations for whom were 24.58 ppb and 26.08 ppb respectively.

2.4.5 Personal Exposure in Buses

One of the most common forms of public transport in both developing and developed nations is buses (Kaur et al., 2007). The provision of efficient public transport networks can prove to be an inexpensive and cleaner alternative to private cars (Wohrnschimmel et al., 2008). Bus Rapid Transit (BRT) systems have been identified as one such popular transportation option. In this section, the impact of such systems and buses on in-vehicle exposure levels will be explored. When considering $PM_{2.5}$ concentration in buses, exposure levels varied between different countries. A study examining the particulate exposure in mini buses and buses in Mexico City, Mexico (Gomez- Peralez et al., 2004) stated that on average, the combined estimate of $PM_{2.5}$ exposure concentrations for both types of vehicles were 68 and 71 μg^3 for morning and evening respectively. An experiment carried out a year later in Trujillo, Peru (Han et al., 2005) showed significantly higher average concentrations with the maximum $PM_{2.5}$ concentration of 161μg^3. Within buses, the presence or absence of ventilation along with the number of decks/levels on buses has an impact on the level of particulate concentration. This can be illustrated by the two studies carried out by Chan et al. in 2002. Chan et al. (2002a) recorded $PM_{2.5}$ exposure levels on non-conditioned double-decker and single-decker buses in Hong Kong, and found the average to be 93 and 96 μg^3 respectively. The exposure to the pollutant on air-conditioned buses was reduced by half. A similar experiment conducted in Ghoungzhou, China (Chan et al., 2002a) reported slightly higher concentration levels: 145±56 μg^3 on non-conditioned buses and 101±61ug/m3 on air-conditioned buses. The flow of open air through open windows also has an impact on the concentration of exposure as shown by Levy et al. (2002): a diesel bus traveling in Boston, Massachusetts with most of the windows open showed similar particulate concentrations as those recorded in Hong Kong and Ghoungzhou. In contrast to the studies already mentioned, the studies carried out in the UK have had much lower exposure concentrations- between 10 and 65 μg^3 to $PM_{2.5}$ exposures (Dennekamp et al., 2002; Kaur et al., 2005). While comparing exposure concentrations between transport modes Tsai et al. (2008) concluded that there were substantial differences in PM_{10}, $PM_{2.5}$ and PM_1 among the different transportation modes, namely commuting by motorcycle, by bus, by car and by Mass Rapid Transit (MRT). The average PM_{10} concentrations for motorcycles were 112.8 μg^3, 70 μg^3 by bus, 64.9 μg^3 by MRT and 41.9 μg^3 by car. $PM_{2.5}$ and PM_1 also followed the same trends with the exposure on motorcycles being the highest, followed by bus, MRT and car. When comparing other pollutant exposures, Chetek et al. (2004) found buses to have the highest exposure levels to NO_2. In comparison, train commuters recorded the lowest. Walking and cycling commuters also had significantly lower levels of exposure to NO_2 when compared to bus commuters. Although Chertok et al. (2004) fail to provide a concrete reason for the high NO_2 exposures in buses, they estimate that the result might have arisen due to the participants commuting on heavily trafficked routes leading in and out of the CBD during peak hours. A study conducted in Amsterdam (van Wijnen et al., 1995) found that for a particular mode, the route taken strongly influenced the NO_2 concentrations for that particular mode.

2.4.6 Personal Exposure in Trains and Subway Systems

Subway systems and trains are major transportation modes typically serving billions of passengers annually in metropolitan areas around the world (Cheng et al., 2008). The air contaminants- either from the outside atmosphere or generated internally- enter the confined underground portion of subway systems thus greatly increasing the concentration levels commuters are exposed to. Several studies have indicated that subway users are exposed to very high levels in particulate matter in cities around the world (Pfeifer et al., 1999; Adams et al., 2001; Johansson and Johansson, 2003). These levels often exceed the PM concentrations generated by traffic emissions in urban air (Cheng et al., 2008). According to Adams et al. (2001), levels of exposure to $PM_{2.5}$ in subway systems are 3-10 times higher than in road transport modes in London. Aarnio (2005) found that average daytime $PM_{2.5}$ levels at underground subway stations were 5-6 times higher than urban background levels in Helsinki. Quite contrary to subway systems, experimental studies suggest that PM_{10} and $PM_{2.5}$ concentrations in above-ground trains are much lower. For example, a study investigating the exposure to pollutants in the Taipei Rapid Transit System (TRTS) reported particulate levels which were lower than Taiwan's Environment Protection Agency standards for indoor air quality proposed in December 2005 (Cheng et al., 2008). The same study found a positive correlation between the indoor station and outdoor levels, indicating that the PM levels in TRTS are significantly influenced by outdoor levels which enter the system through the ventilation systems, station escalator tunnels and corridors. Park et al. (2008) also found that the concentrations of PM_{10} and $PM_{2.5}$ inside trains were found to be slightly higher than those measured on platforms. Also, particulate concentrations monitored from underground stations were significantly higher than those on ground stations, thus indicating that subway environments are heavily polluted with fine particulates.

When comparing pollutant exposures in train to exposures in other modes of transport, Chan et al. (2002) found that, in comparison to non-air-conditioned roadway transport (147 μg^3) and marine transport (81 μg^3), railway transport commuter has the lowest (50 μg^3) PM_{10} exposure levels. Similar results were also obtained for exposures to $PM_{2.5.}$

While air-conditioned roadway transport had lower PM_{10} levels which were lower than non-air-conditioned ones, PM_{10} levels found air-conditioned road vehicles were still higher than the levels in railway systems. The low levels could be attributed to the fact that railway systems have their own tracks, which are often located away from busy roads and other traffic. Furthermore, they draw less polluted air from the top of the compartment (Chan et al., 2002).

Chertok et al. (2004) studied the exposure levels for BTEX pollutants and NO_2 in different modes of transport and found that the lowest BTEX exposure concentration was found for train commuters, followed by walking, cycling and bus. These results indicate that non-roadway mode and modes involving physical activity are good alternatives to cars to reduce personal exposure to BTEX pollutants. The results obtained for NO_2 exposures were similar, in that train commuters had considerably lower levels of exposure to NO_2 compared with other modes. The clearly lower exposure levels for train commuters could be attributed to the fact that train commuters are not directly exposed to the roadway micro-environment.

As has been discussed, many studies have been conducted to investigate the pollutant exposure in different modes of transport. However, exposures to traffic pollutants in micro-events have not been studied as thoroughly. The next section will review a range of scientific literature which will focus on the short-term pollution exposure in micro-spaces, and will investigate the contribution events in micro-environments to commuter exposures.

2.5 Short- term Exposure in Micro- environments

2.5.1 Introduction

Air quality standards for pollutants are based on outdoor averaged levels of pollution (Dor, 1995). Yet there is evidence that pollution exposure varies both spatially and temporally (Kingham et al., 1999). A “hot spot” of air pollution can be defined as an ‘area where the average concentrations of air pollutants are higher than those in surrounding areas.’ (Zhu et al., 2008 p. 7329). Past research has shown that in such “hot spots”, localised concentrations of air toxins can occur due to large or small emission sources (Sweet and Vermette, 1992; Hung et al., 2005, Smith et al., 2007). It is important to gain an understanding of the spatial and temporal distribution of air toxins in a “hot spot” for conducting accurate assessment of personal pollution exposure (Burnett et al., 2001; Leikauf, 2002; Jerrett et al., 2005; Weis et al., 2005).

2.5.2 Spatial and Temporal Variation in Commuting Journeys

Several scientific research projects have suggested that personal exposure to pollution levels depend on temporal and spatial changes on journeys (Kingham et al., 1999; Zhang et al., 2006; Cheng et al., 2008). A report published by the World Health Organisation (2005) similarly contends that pollution levels are affected by the volume and spatial distribution of emissions, as well as its dispersion conditions. The publication further reports that pollution intake is also determined by how long people stay in polluted areas and what they do there. A vast amount of research has been conducted to measure commuters’ personal pollution exposures on different transport modes (Alm et al., 1999; Praml and Schierl, 2000; Chan et al., 2001). However; there has been little scientific work done to investigate pollution level variations within a journey that might lead to commuters being exposed to short-term peak levels of pollutants while commuting. For instance, commuters spend a part of their commuting journeys in car parks, bus stops/ stations, metro subways and train stations. Although they might only spend a fraction of their total journeys in these micro-environments, scientific evidence has demonstrated that there are very high levels of pollutants in these environments (Chau et al., 2000; Adams, 2001; Aarnio, 2005; Park et al., 2008; Tsai, 2008). These authors suggest that individuals, thus, gain a significant contribution of their daily exposure in a short period of time. The next three sections will discuss the pollution exposure in such confined spaces such as sheltered car parks, bus stations and subways which might elevate commuters’ level of personal pollution exposure.

2.5.2.1 Bus Stations

Bus stations are similar to car parks and train and subway stations in that they are all confined spaces. It would then be safe to assume that bus stops might have higher levels and concentrations of pollutants compared to non-confined open areas. Kingham et al. (1999) carried out an experiment in West Yorkshire where they measured pollution exposure of individuals while travelling on a bus and compared the results to time-activity data collected through the use of journey diaries. The result (Figure 2.2) shows that certain activities, such as getting on the bus and waiting at the bus stop greatly increases PM exposure levels.

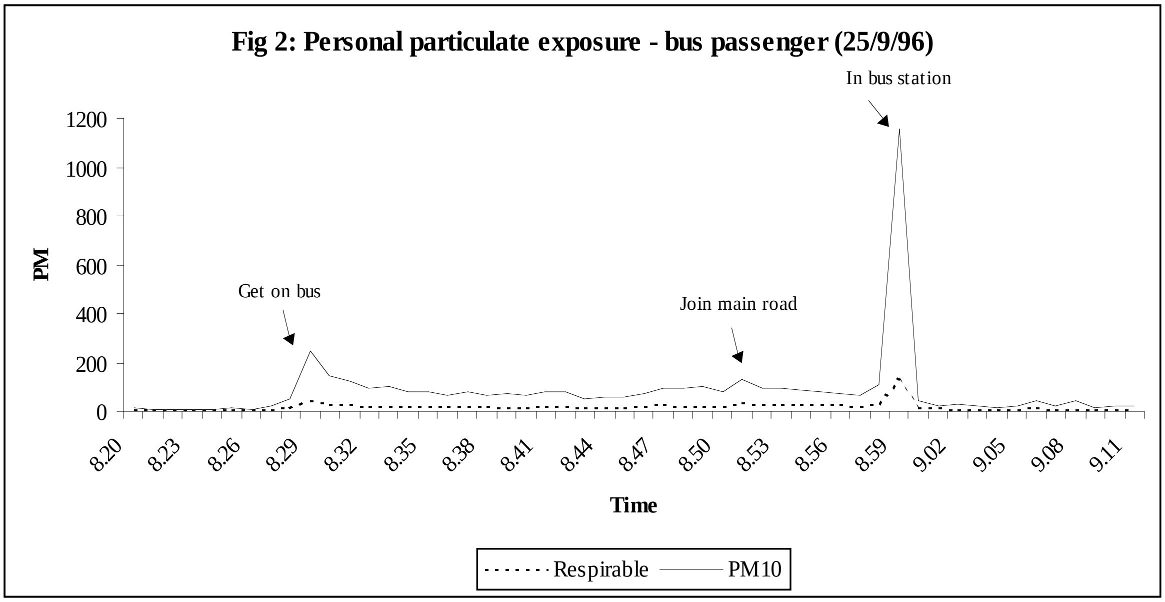


Figure 2.1 Particulate Peaks on a bus journey in West Yorkshire

Source: Kingham et al. (1999)

A potential explanation for such high elevations when entering the bus and while waiting at bus stops has been provided by a study comparing commuters' exposures to particulate matters while using different modes of transport (Tsai et al., 2008). They report that the physical distance between commuters and traffic-related emission sources may explain why bus commuters have a relatively high particulate exposure: bus commuters are potentially exposed to $PM_{2.5}$ and PM_1 emitted from vehicles passing by when they are waiting at roadside bus stops.

2.5.2.2 Car Parks

Very high concentrations of CO and other pollutants have been recorded in poorly ventilated, confined spaces used by motor vehicles (Flacshbart, 1999). Studies done as early as the late 60s reported higher than average levels of CO concentrations in garages (Trompeo et al., 1964; Chovin et al., 1967). Goldsmith (1970) found that large numbers of cars queuing to leave parking buildings could elevate pollution levels inside garages to extremely high concentrations. A later study (Barker and Fox, 1976) conducted tests inside garages using indicator tubes. This showed instantaneous concentrations of up to 210 ppm. Further tests revealed even higher levels for short periods. More recent research reiterates these findings (Chau et al., 2002; Papakonstantinou et al., 2003). Duci et al. (2000) claim the garage micro-environment to be a very important determinant of exposure to CO. Experiment carried out in an urban section of Athens to measure CO levels in garages found that there were increases to short and long term exposure limits to CO (Chaloulakou et al., 2002). This can be attributed to poor or malfunctioning ventilation inside, which allows contaminated air to accumulate and pollutant concentrations to increase.

2.5.2.3 Subway Systems and Train Stations

'Commuters tend to spend only a short fraction of their day in the metro, but if the levels of particulate matter and its elemental composition in the metro are high, even short durations can contribute a lot to the total exposure of a person, and any related health effect' (Nieuwenhuijsen et al., 2007, p.8001). Subway systems serve millions of passengers annually worldwide. The underground portion of a subway system is a confined space with concentrations of pollutants influenced either by the outside atmosphere or generated internally (Cheng et al., 2008). A multitude of scientific studies worldwide corroborate these findings. High concentrations of particulate matter have been measured in subway systems in London (Pfeifer et al., 1999; Adams et al., 2001), Stockholm (Johansson and Johansson, 2003), Berlin (Fromme et al., 1998) and Beijing (Li et al., 2007). The studies conducted in London further reported that $PM_{2.5}$ exposure levels in subway were 3-10 times higher than in road transport modes in London (Adams et al., 2001). Similarly, Johansson and Johansson (2003) found that PM_{10} and $PM_{2.5}$ levels at an underground station were 5 and 10 times, respectively higher than those measured at the busiest streets in Central Stockholm. Ripanucci et al. (2006) also observed that average PM_{10} levels in the underground platforms were 3.5 times the average level above ground.

It has been established that diesel locomotives emit considerable amounts of air pollutants in a short time, and emissions are usually confined to a small area (WHO, 2005). Measurements of the air quality in and around railway stations were published in a French study conducted in Paris (Keuken et al., 2005). It reported that, on average, within a 1000-m radius of the station, the diesel trains emit about 16% of total NO_2 and 9% of PM. These figures escalate to 50% of total NO_2 and 33% of PM at peak times. Depending on wind direction and speed, the train plumes can lead to peak nitrogen dioxide concentrations of 750-1200 μg^3 at 200-400 meters from the rail tracks. Although the levels declined after the train departured, they remained above 25% of the total concentration for up to nine minutes. A study carried out in West Yorkshire (Kingham et al., 1999) repeated these findings. The project measured pollution exposure of individuals while travelling on different forms of transport and compared the results to time-activity data collected through the use of journey diaries.

Figure 2.1 below shows the result for a commuter train journey from Marsden to Huddersfield in West Yorkshire. Particulate peaks can be seen to relate to a variety of journey features such as the train stopping at stations and the subject walking through the station.

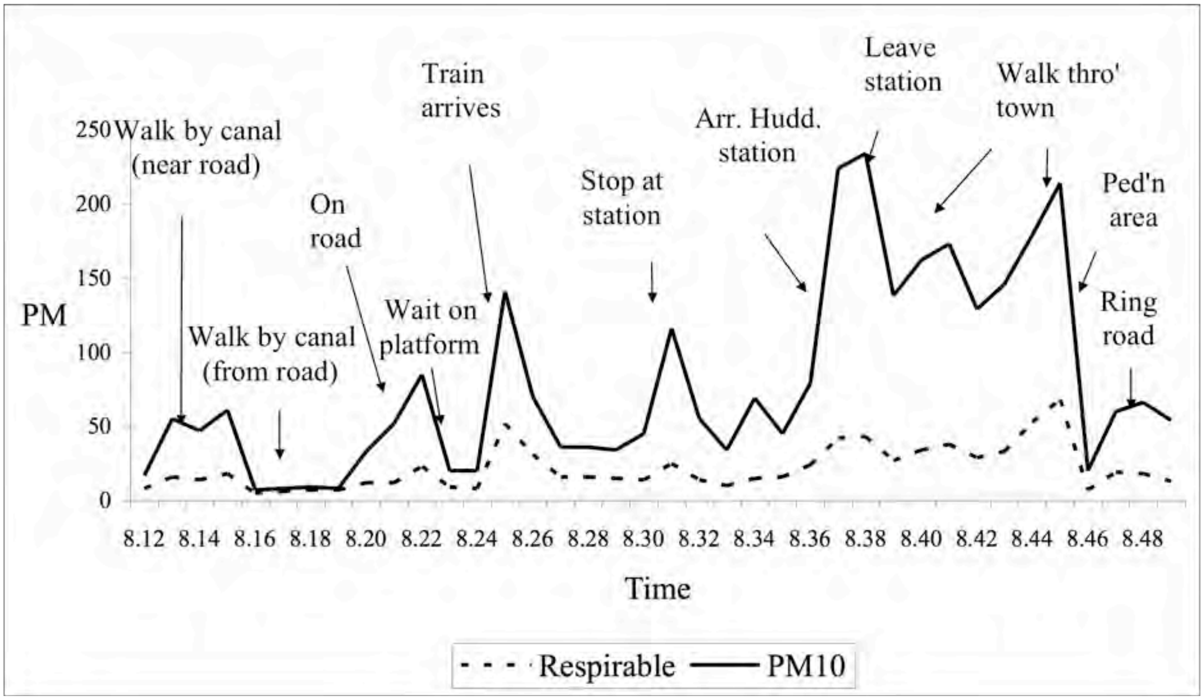


Figure 2.2 Particulate peaks on a train journey in West Yorkshire

Source: Kingham et al. (1999)

2.6 Short-term Peak Exposure and its Health Effects

As is apparent from the literature discussed, commuters spend a part of their journey in car parks, train stations, subways and bus depots/ stops. Although the time spent in those locations cover only a small percentage of the total journey, commuters are exposed to high concentrations of pollutants in a very brief period. In epidemiological studies of chronic health effects, it is common to use exposure indices which do not reflect peak exposures (Preller et al., 2004), with most studies collecting 24-or 8-hour samples. Although recent studies have established that exposure to short term peaks in PM pose especial health threats, only a few studies have evaluated the relationship between personal pollutant exposure and micro-environments with high-level time resolution (Quintana et al., 2001). One such study (Quintana et al., 2001) documented that very high PM levels occurred in relatively few of the minutes measured but comprised of a substantial amount of the total PM exposure. The study further noted that fifteen-minutes averaged PM levels were found to be as high as ten times the daily average. Another study reported that adverse health effects associated with air pollution may be attributable to short-term (a few minutes) exposure. For instance, asthmatics exposed to SO_2 may experience effects within minutes (Cairncross et al., 2007). Another experiment compared peak and average nitrogen dioxide concentrations to test whether long-term passive monitors provide adequate information on short- term peaks, which may be important when examining health effects of pollutants (Franklin et al., 2006). Though this study measured concentrations inside homes, the results are applicable when comparing long- term averages to short- term peaks in transport micro-environments. The study reported that peak NO_2 concentrations inside homes exceed 3000 μg^3 when gas appliances have operated (Goldstien and Andrews, 1987), however, as Franklin et al. (2000) contend, the relationship between short-term peaks and long-term average NO_2 concentrations has not been properly investigated in previous studies. The study found long-term averages for concentrations inside home ranged from below detection levels (BDL) to 47.3 μg^3. The short- term NO_2 concentrations, on the other hand, ranged from BDL to as high as 243.1 μg^3. It is imperative to realise that these short-term peaks may be very important when examining health effects of pollutants.

To conclude, commuters tend to spend only a short fraction of their time in metro and subway stations and sheltered/underground car parks, but if the levels of particulates and other pollutants in these locations are high, even short durations can contribute significantly to the total exposure of a commuter, and any related health effects (Seaton et al., 2005).

2.7 Meteorological Conditions

Besides the mode of transport, meteorological factors can influence personal exposure concentrations in the urban transport environment (Kaur et al., 2007). The most important factors to consider include wind speed, relative humidity and temperature (Morawaska et al., 2008). Amongst all these meteorological variables, the effect of wind speed on personal pollution exposure has been the most closely studied. Not only does wind speed affect dispersion and dilution of pollutants, but also resuspension of particles (Morawaska et al., 2008). Various exposure and ambient studies have shown that an increase in wind speed leads to a decrease in exposure concentrations in particulate matter and CO (Bevan et al., 1991; Kingham et al., 1998; Holmes et al., 2005). Perales et al. (2004) also reported a reduction of 22 and 24% in $PM_{2.5}$ concentrations for every 1m/s increase in wind speed in minibuses and buses respectively. With respect to ultrafine particle concentrations, Kaur and Nieuwenhuijsen (2009) reported that wind speed was a significant determinant ($p<0.0\ 5$) of UFP exposure concentrations. Other studies examining ultrafine exposure concentrations in windy weather have also reported lower count concentrations at higher wind speeds (Molnar et al., 2002; Krausse and Mardeljevic, 2005). Although studies have been carried out to investigate the impact of other meteorological conditions on pollutant exposure levels, most have found no effect. For example, Koushki et al. (1992) and Zagury et al. (2000) found no correlation between temperature and CO and UFP concentrations. However, there have also been some conflicting research results, which have identified temperature as a significant determinant of UFP count, and CO exposure counts (Kaur, 2006). Fixed monitoring sites have also identified relationships between CO/ultrafine particle concentration levels and temperature (Elminir, 2005; Nanzetta and Holmen, 2004). Although commuters can do little to affect meteorological factors, they may use this data to choose the time to travel (for example, stay indoors in calm conditions) to help reduce their personal exposure (Kaur and Nieuwenhuijsen, 2009). Furthermore, city planners could use these findings to design cities which allow more airflow through the city to cut down pollution levels.

2.8 Summary

Increases in both global population and energy consumption have led to air pollution being rapidly recognised as a major environmental and public health issue in both developing and developed nations. It is well established and widely accepted that air pollution from transport sources has adverse effects on numerous health outcomes including mortality, morbidity and hospital admissions (Kingham et al., 2007). Not only does transport related air- pollution increase the risk of death from cardiopulmonary causes, it also increases the risk of respiratory symptoms and diseases that are not related to allergies. Vehicle emissions can be labeled as one of the most important source for some pollutants of great concern such as carbon monoxide, nitrogen dioxide, volatile organic compounds (VOCs) and particulate matter. Various studies have been carried out to analyse the exposures to air pollution by comparing different modes of transport. Investigations in a number of cities around the world have shown that exposure to air pollutants for commuters in motor vehicles is considerably higher than ambient urban concentrations, and higher than concentrations found in other urban transport modes such as train, bus, cycling and walking. Besides the mode of transport, meteorological factors can influence personal exposure concentrations in the urban transport environment. Various exposure and ambient studies have shown that an increase in wind speed leads to a decrease in exposure concentrations in particulate matter and carbon monoxide. Although a lot of research has been devoted to studying personal exposure on different modes of transport, there has been little scientific work done to investigate pollution level variations within a journey that might lead to commuters being exposed to short- term peak levels of pollutants while commuting. Scientific reports suggest that individuals, thus, gain a significant contribution of their daily exposure in a short period of time in micro- environments such as cars parks, bus stops, underground subways and train stations even though commuters might only spend a fraction of their total journeys. It is, however, very important to realise that even short durations can contribute significantly to the total exposure of a commuter, and any related health effects.

CHAPTER THREE

Research Area

3.0 Introduction

The purpose of this chapter is to introduce the physical setting and the demographics of the study areas. First, a brief overview of New Zealand will be presented. This will be followed by a discussion of the specific study areas, namely Christchurch and Auckland (Sections 3.3 and 3.4 respectively). Each will be presented as a separate case study with an analysis of the region's topography and meteorology. In addition a thorough examination of the quality of air in both cities will also be included.

3.1 New Zealand and Air Pollution: The National Context

3.1.1 Brief overview

New Zealand is located in the southwest Pacific Ocean at approximately 41°S and 174°E. Australia and Antarctica are the nearest continental land masses at distances of 2000 and 2500 kilometers respectively (Bury, 2001). 'Internationally, New Zealand has a reputation for having a pristine environment with plenty of green spaces and lots of fresh, unpolluted air' (Zawar- Reza et al., 2004, p. 249). In reality, however, air pollution is a serious environmental problem, especially in urban regions (Fisher et al., 2007). As in many developed countries, the intensity of human activities has a major impact on New Zealand's ambient air quality with home heating being the greatest anthropogenic influence on outdoor air quality. In winter, approximately 45% of New Zealand households burn solid fuels for heating their homes (Ministry for the Environment (MfE), 2007). In 2005, MfE reported that while 32 per cent of Auckland households rely on coal and wood for home heating, this figure rises to over 75 percent on the West coast of the South Island (MfE, 2005). The effects of vehicle traffic on local air quality have received increasing attention since 1996 (Irving and Moncrieff, 2004). Regular air-quality monitoring in the main cities (Christchurch and

Auckland) has given rise to concerns over the level of certain air pollutants commonly associated with motor vehicle exhaust emissions (Ministry of Transport, 1998), with New Zealand having one of the highest rates of private vehicle ownership in the world (MfE, 2007). Covec (2005) asserts that older and high mileage petrol cars are more likely to be high emitters of pollution than newer vehicles. The average age of New Zealand motor vehicles is 12.4 years, and nearly two- thirds of the newly registered vehicles are used imports rather than new vehicles.

3.1.2 Traffic Air Pollution and Health

The European Environment Agency (2005, p.7) concluded:

> *"Air Pollution is the environmental factor with the greatest impact on health in Europe and is responsible for the largest burden of environment-related disease."*

The link between air pollution and health was weakened in the 1970s following an abatement in research on air pollution concentrations in the 'developed world' (Holland et al., 1979). Since then, however, the tremendous increase in motor vehicle traffic has led to the re-emergence of air pollution as a major environmental health issue (Brunekreef and Holgate, 2002). Emissions from transport, industry, domestic and other human activities have major effects on health worldwide (Fisher et al., 2007). It is widely accepted that air pollution from transport sources has an adverse effect on health including mortality, morbidity and hospital admissions (Kingham et al., 2007). Motor vehicle emissions have led to extremely high concentrations of particulate matter, carbon monoxide and nitrogen dioxide. The 2007 Health and Air Pollution in New Zealand (HAPiNZ) report identified domestic heating as the major contributor of air pollution that harms human health (Figure 3.1). However, nearly half of the total cases of premature death due to CO, PM_{10} and NO_2 can be attributed to air pollution from vehicles, which is also the largest cause of cancer related to air pollution (Air Quality Report Card, 2009). The HAPiNZ study (Fisher et al., 2007) also identified an overwhelming economic cost of urban air pollution costing 1.14

billion dollars every year and 285,000 restricted activity days that occur during periods of poor air quality.

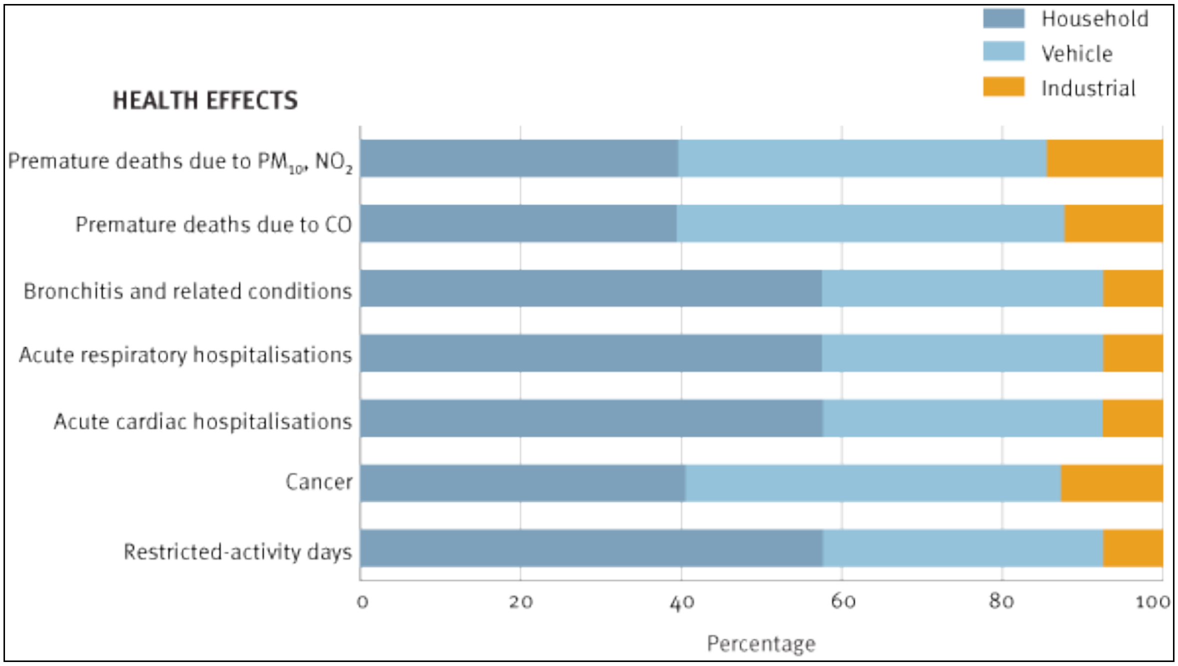


Figure 3.1 Health effects of air pollution in New Zealand, by source and effect, 2001 (proportion of cases in the population over 30 years of age)

Source: Air Quality Report Card, Ministry of Environment, February 2009

3.2 New Zealand Legislation

3.2.1 History of air pollution legislation

During the last century, anthropogenic activity has been one of the most significant perpetrators of climate change over a relatively short period of time (Karl and Trenberth, 2003). Rapid decisions need to be made in order to minimise the impacts of transport on the environment and the health of a population (Chapman, 2007). The 1950s saw a sharp rise in epidemiological studies that associated air pollution with detrimental health effects (Bell et al., 2004). In response, many countries around the world, including New Zealand, have developed national guidelines to ensure a guaranteed level of protection for human health.

3.2.2 New Zealand's national air quality guidelines and standards

The 2007 Environmental New Zealand Report (2007, pp.11) declares that 'people who make decisions about the environment need accurate and reliable environmental information, with which they can make informed decisions about national resource management and environmental policy'. The Resource Management Act (RMA), passed in New Zealand in 1991, regulates access to physical and natural resources and aims to ensure sustainable management of such resources, including air. Under the guidance of the RMA 1991, the Ministry for the Environment introduced national environmental standards (NES) for air quality (MfE, 2009) in 2005. These guidelines represented minimum values, which were required to ensure the protection of human health and the environment. In September 2005, five ambient standards for air quality came into effect (MfE, 2007). These standards dictate national maximum thresholds for five key air pollutants, including PM_{10} particulates, NO_2, CO, SO_2 and ground-level ozone. It is important to note that air quality in New Zealand is affected by pollutants other than those listed by the Resource Management Act (1991) Regulations. These pollutants, which include $PM_{2.5}$, benzene and lead, have reached elevated levels across New Zealand in the past (MfE, 2007).

It has been established that the NES for air quality were introduced in New Zealand to 'provide a guaranteed level of protection for health' (Air Quality (Particulate Matter-PM_{10}) Report Card, MfE, 2009; pp. 2). Although these environmental standards and guidelines are a means of curbing the rising air pollution in New Zealand, care must be taken when making assumptions of their actual effectiveness to protect health. Exposure estimates from fixed monitoring sites (FMS) are known to be the basis of air quality guidelines and policy (Kaur et al., 2007), however, many studies have revealed that measurements from FMS significantly underestimate or have no association with the exposure of population sub-groups (Chan and Wu, 1993; Adams et al., 2001; Alm et al., 2001). Scientific evidence corroborates that urban background FMS significantly underestimates the exposures experienced by people in the transport microenvironment (Kaur et al., 2007). Personal exposure is strongly influenced by factors such as personal activities, proximity to pollutant sources and individual movement; however, the ambient guidelines do not account for these factors (Longley, 2009). For instance, experiments comparing outdoor ambient levels to metro station PM levels discovered that levels of exposure to particulate matter in subways were 3-10 times higher than in road transport modes in London (Adams et al., 2001). Similarly, Aarnio et al. (2005) reported average daytime $PM_{2.5}$ levels to be 5-6 times higher than the urban background levels in Helsinki. This discrepancy between personal exposure (true value of the variable) and ambient levels (assumed value) is termed 'exposure misclassification error' (Thomas et al., 1993). Using measurements from central ambient sites to account for personal exposure may lead to an underestimation of health effects of air pollution.

In addition to the issue of such 'exposure misclassification error', NES does not include indoor pollution. This is of special concern since people spend a substantial portion of their time indoors (Ashmore and Dimitroulopoulou, 2009). Furthermore, commuters also spend a fraction of their time indoors in micro-environments such as sheltered and underground car parks, indoor bus stops and metro stations. Scientific evidence has shown that indoor air quality is closely linked to personal exposure; the importance of air pollution in the built environment and its effect on health was recognised as early as 1960 when occupants of residential, commercial and institutional buildings reported health problems (e.g. eye and respiratory irritation, breathing difficulties or asthma) associated with their buildings (Kreis, 1989). It is, therefore, essential to understand how indoor air quality affects personal exposures to assess policy interventions to reduce adverse health effects (Ashmore and Dimitroulopoulou, 2009). Secondly, the synergistic effects from exposure to two or more pollutants are also not shown. Finally, the influence of weather and climate when reporting air quality is not taken into account. This makes it difficult to assess whether changes in levels of air pollution can solely be attributed to changes in emission levels of pollutants. Also, more sophisticated monitoring techniques and statistical methods have established that adverse health effects can result from pollution levels below the ambient guidelines (Dockery and Pope et al, 1994). Furthermore, the World Health

Organisation has declared that there is no zero-effect threshold for particulates, and that health risks are present at any level of exposure (World Health Organisation, 1999).

3.3 Case Study One: Christchurch City

3.3.1 Introduction

With a population of 330,000, Christchurch is the largest city in the South Island of New Zealand (Barna and Gimson, 2001; Wilson et al., 2005). It is located on the Canterbury Plains, situated about 70 km east of the Southern Alps (172° 37′ W -43° 31′ S) and north of an eroded volcanic crater known as the Banks Peninsula (Figure 3.2). The convergence of cold air drainage from the Southern Alps with the localized cold air drainage winds from the peninsula is thought to be responsible for generating zones of stagnant air which enhances temperature inversions on cold winter nights (Koss and Sturman, 2004).

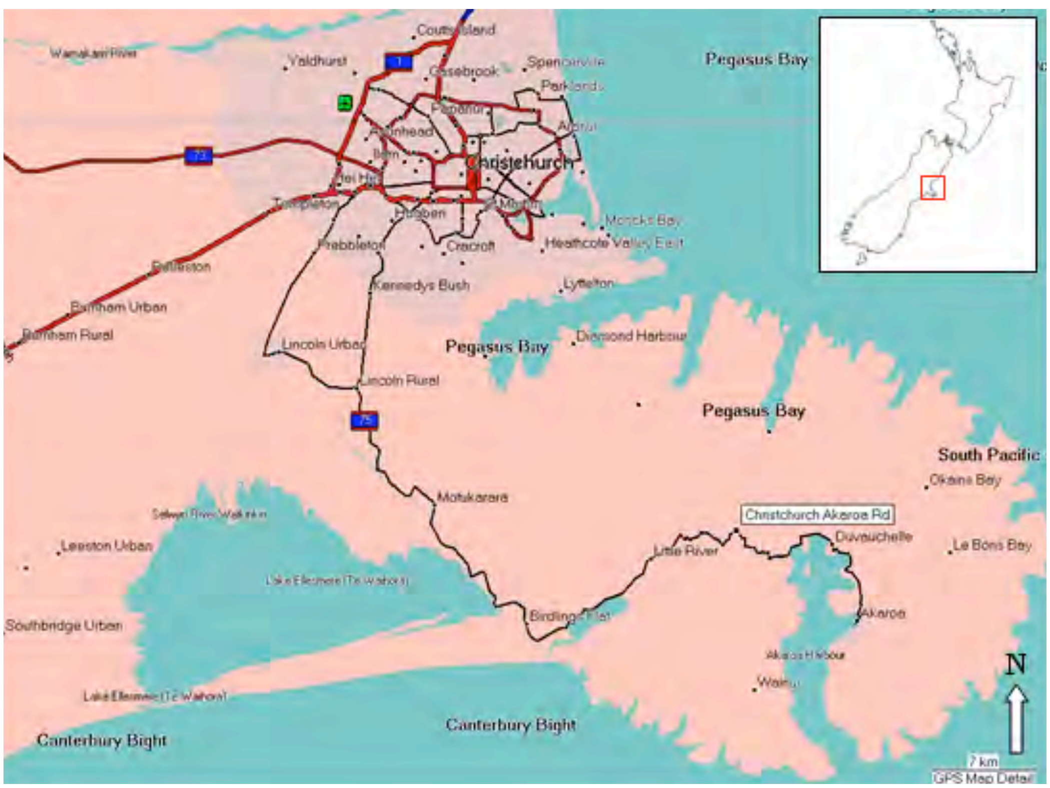


Figure 3.2 *Map of the Christchurch region*
Source: www.travelpod.com [accessed 24 July 2009]

3.3.2 Air quality in Christchurch

High air pollution episodes during winter are generally well known in Christchurch. Approximately 48% of Christchurch homes burn coal or wood as a main source of heating on a typical winter day and/or night (Lamb, 2003). Out of a total of 13.2 tonnes of PM_{10} discharged on a typical winter day, 11.2 tonnes are sourced from domestic heating (Scott and Gunatilaka, 2004). An environmental report published by MfE in 2007 reported that of the five main centres of population, Christchurch experiences some of the highest peak levels of PM_{10} particulates, mostly during winter temperature inversions. Monitoring at the residential St. Albans site showed that there were more than 50 exceedences per year recorded in 1999 and 2001. Ambient 24-hr averages of PM_{10} exceed the national ambient air quality guideline of 50 μg^3 30 times every winter (Aberkane et al., 2004). Transport emissions account for 12.5% of the particulate matter in Christchurch (MfE, 2007). Most particulate monitoring in New Zealand has been for PM_{10} particulates rather than $PM_{2.5}$. However, monitoring has shown that the relationship between $PM_{2.5}$ and PM_{10} varies during the year. Christchurch monitoring has indicated that the particulate levels are similar in winter, but vary in summer. During winter, both particulates in Christchurch come mainly from combustion sources such as home heating so levels are more similar (MfE, 2007). $PM_{2.5}$ particulates are more likely to exceed NES than PM_{10} in Christchurch. For example, there were 49 exceedences of $PM_{2.5}$ compared to 37 of $PM_{10.}$

Transport is still the main source of CO in Christchurch. Emission estimates indicate that vehicle exhaust contributes 51% of winter emissions in metropolitan Christchurch (MfE, 2007). Private vehicle ownership and road congestion increased in the urban areas of Christchurch between 1999 and 2001, however CO emissions from motor vehicles fell by 15%. This is thought to have resulted from the increasing number of vehicles with emissions control equipment (MfE, 2004). Levels of NO_2 in residential areas of Christchurch indicate good air quality. As with CO, transport is also the main source of NO_2 in Christchurch, however estimates of oxides of nitrogen emissions from motor vehicles in Christchurch have decreased by 5%. This is in spite of a 12%

increase in the number of vehicle kilometers travelled. Again, this is thought to result from an increase in the number of vehicles with emission control equipment in the region (MfE, 2004).

3.3.3 Transport in Christchurch and its Implications

The Christchurch public transport system is based principally around buses, and the services are administered by the regional council, Environment Canterbury. The Regional Environmental Report (Environment Canterbury, 2009) reported that motor vehicles remain the main mode of travel throughout Canterbury despite an increase in public transport patronage. The growth in the transport sector and the resulting congestion in the region have been key issues for Environment Canterbury in 2009. A report published by the Urban Development Strategy (Report #1) stated that traffic volumes in the city are projected to increase by 40- 50%, with over 1.8 million journeys made by vehicles each day by 2021. The publication also reported that Christchurch has a high number of registered private cars with 59 cars for every 100 people. The number of registered vehicles is estimated to increase by 40- 50% within twenty years. 12% of the city's population travels by walking, cycling and other public transport. Within Christchurch, the 2001 census information showed that while 77% of people drove cars to work, 4% of the population used the bus. To reiterate the results from scientific studies done in the past, the differences in variations in pollution exposure during a journey are very large (Kingham et al., 1999). For instance, certain features of the journey have a significant effect on levels of particulate exposure. Elevated levels in personal exposure have been identified in bus stops, and also in sheltered car parks over short periods of time (Chau et al., 2002; Papakonstantinou et al., 2003; Kingham et al., 1999). Since a large percentage of Christchurch's population use cars and buses for transportation, it is inevitable that they are exposed to such high pollution levels in exposures in micro-environments. Therefore, it is essential to understand the nature of short-term peak exposures on commuters, and related health effects.

3.4 Case Study Two: Auckland City

3.4.1 Introduction

Auckland is the largest city in New Zealand with a population of 1.2 million (Senaratne and Shooter, 2004). Situated on an isthmus with harbours to the west and east (Figure 3.4), Auckland is exposed to weather systems from both sides of New Zealand (Wang and Shooter, 2005). With the Pacific Ocean to the east and the Tasman Sea to the west, Auckland is exposed to relatively clean air and frequent light winds (Clarkson and Fisher, 2000). Occasionally, under specific weather conditions, namely cold and calm winter mornings and nights with diurnal opposing onshore sea breezes, the city experiences a significant rise in pollution levels. This leads to a build-up of a brown haze, aptly termed ‘urban haze’ in the central city and to the west and the south of the region (Auckland Regional Council, 1997). Past research has indicated that the reddish brown colour in the smog is due to the presence of NO_2 in the air (Jacobson, 2002), however a more recent study (Senaratne and Shooter, 2004) revealed that diesel and petrol emissions were the highest contributors to the build up of brown haze.

Figure 3.3 *Map of the Auckland Region*
Source: www.travelpod.com [accessed on 24 July 2009]

3.4.2 Air quality in Auckland

Every Auckland citizen breathes in 11,000 litres of air everyday (ARC, 2009). In spite of the region's relatively good air quality, 436 Aucklanders die prematurely due to air pollution every year. More than half of these can be attributed directly to pollution from vehicle emissions (ARC, 2009). One of the major sources of air pollution within the Auckland region is motor vehicles. Transport emissions account for 64% of particulate matter in Auckland's air with 73% of PM_{10} particulate emissions from motor vehicles coming from diesel exhausts alone (MfE, 2007).

Levels of CO in Auckland have been shown to decrease over the past ten years; however, transport is still the main source of pollution in Auckland. Estimates indicate that 85% of annual CO emissions are due to vehicle exhaust (MfE, 2007). As with particulate matter and CO, recent trends in NO_2 show that transport is the main source of oxides of nitrogen in all main population centres, accounting from almost 90% of emissions. Auckland has seen a rise in NO_2 emissions since 1998 due to an increasing fleet of diesel vehicles in the region (ACR, 2006b).

3.4.3 Transport in Auckland and its Implications

According to the figures published by the Auckland Regional Council (2009), there are 865,000 vehicles in Auckland traveling about 12,500,000 km s^{-1} every year. Traffic emissions from these vehicles are responsible for producing thousands of tonnes of toxic air pollutants, especially fine particles, CO and NO_2. The public transport in Auckland is managed by the Auckland Regional Transport Authority (ARTA) and consists of buses, trains and ferries. According to the ARTA, over 50 million passenger trips are made in Auckland each year (ARTA, 2009), which makes the Auckland transport system the largest in New Zealandby total passenger volume. While buses are the most widely used form of public transport in Auckland, the city also has a commuter rail system which uses diesel- powered trains. Britomart, one of the few underground railway stations in the world, is designed to serve 10,500 passengers during the peak hour (Britomart Transport Centre). According to the Auckland Regional Transport Authority, rail patronage increased from 2.5 million journeys in 2003 to 5.7 million in the year ending 2007, and there have been concerns that the station will soon reach its maximum capacity. This is of concern since the underground portion of a subway system is a confined space that may promote the concentration of contaminants either from the outside or generated internally. Scientific evidence corroborates that subway commuters are exposed to even higher levels of PM than urban air (Pfeifer et al., 1999; Sitzmann et al., 1999). As has been established before, exposure to airborne particulate matter results in adverse health effects such as cardiovascular and respiratory diseases (Pope et al., 2002). This alludes to the fact that millions of commuters who use the underground station in Britomart are exposed to particulate pollution.

3.5 Summary

Air pollution is a serious environmental problem in New Zealand, especially in the urban regions. While home heating contributes significantly to the worsening quality of air in New Zealand, regular air- quality monitoring in the main cities (Auckland and Christchurch) has given rise to concerns over the level of certain air pollutants commonly associated with motor vehicle exhaust emissions. It is widely accepted that air pollution from transport sources has an adverse effect on heath on numerous occasions including mortality, morbidity and hospital admissions and motor vehicle emissions have led to extremely high concentrations of particulate matter, carbon monoxide and nitrogen dioxide. In response, New Zealand, like many other countries around the world, developed national guidelines to ensure a guaranteed level of protection for human health. However, care must be taken when making assumptions of how effective these guidelines actually are. Such general guidelines usually do not reflect the high levels of peak exposures found in transport micro-environments such as bus stations, subways and sheltered car parks. It is essential to consider the implications of short- term peak exposures in such micro-environments as an increasing percentage of New Zealand's population rely on cars, buses and trains to commute on journeys. This means that a growing number of people in both Christchurch and Auckland spend a portion of their commuting journeys in sheltered car parks, bus stops and underground subway stations may which contribute significantly to their total daily exposures, and consequently, their health.

CHAPTER FOUR

Methodology

4.1 Introduction

The purpose of this chapter is to outline the methods undertaken to meet the requirements of the thesis aims presented in chapter one. This section will present a concise description of the sampling areas and will discuss the sampling design and equipments used. A brief discussion of the pre-fieldwork tests and preparation set up will also be included. Finally, this chapter will conclude with an overview of the statistical tools and methods employed for the analysis of the results gathered. The overall aim of the method was to compare the pollution exposure on different modes of transport. More specifically, the objective is to measure peaks and troughs in personal pollution exposure during short commuter journeys in cars, buses and trains.

4.2 Equipment and Tools

4.2.1 Sampling Equipment

A variety of pollution monitoring equipment was used. All were portable and carried by individual commuters for the purposes of personal pollution exposure sampling. Table 4.1 presents a comprehensive list of the sampling equipments utilized during the fieldwork. The photographs of the individual sampling units are included in the appendix.

Table 4.1 *Sampling Equipments used and Pollutants monitored*

Equipment	Brief Description	Pollutant Measured	Time Resolution
GRIMM 1.107 Dust Monitor	Portable Environmental Dust Monitor which measures particulate matter using an optical scattering technique	PM10 PM2.5 PM1	6- seconds
TSI 3007	Particle counter which counts ultrafine particles by condensing an alcohol vapour onto its surface until it is big enough to be counted optically	Ultrafine particles	1-second
Kestrel 4500	Pocket weather tracker	Temperature and Humidity	1-second
Langan Model T15n	CO Measurer is a real time CO analyzer. It has an electrochemical sensor optimized to observe carbon monoxide in the 0 to 200 parts per million (ppm) range with a resolution of 0.005 ppm (50 ppb)	Carbon Monoxide	1-second
Nokia N82	Mobile phone equipped with a GPS receiver, navigations software and a five-mega pixel camera	NA	3-seconds

4.2.2 Sampling Kit

Portable sampling kits were custom- made to hold all the sampling units while carrying out the air pollution monitoring (Figure 4.1). While the kestrel, the Nokia N82, and the Langan T15n were placed in compartments in front of the kit, the GRIMM Dust Monitor and the TSI 3007 were kept inside the bag. Stainless steel pipes were attached to the GRIMM and the 3007. These pipes faced forward and protruded out of the kits to allow proper sampling of the air. While the bus and train commuters placed these kits on their laps in front of them, and the car driver placed it on the passenger seat. Special metal brackets were placed in front of the bicycle handles to accommodate the mobile sampling units (Figure 4.2)

Figure 4.1 *Portable sampling kit used for air pollution monitoring*

Figure 4.2 *Custom-made metal brackets for holding sampling unit on bicycle*

4.3 Sampling Areas

Fieldwork was carried out in two major cities in New Zealand, namely Christchurch and Auckland. The relatively flat topography of Christchurch, along with a high number of cyclists assisted in establishing clear relationships between transport modes and pollution exposure. The Christchurch sampling was completed before the onset of winter in 2009 to lower the influence of domestic emissions on air pollution. The heightened traffic pollution in Auckland and its large population, along with its rail network and the Northern Busway- New Zealand’s first purpose built road dedicated to bus passenger transport, and a key part of Auckland's rapid transit network- made Auckland an ideal sampling location.

4.3.1 Christchurch City

Fieldwork commenced in Christchurch on 26 February 2009 and ended a month later on 26 March. The selected modes of transport were car, bus, and two bicycles. While one cycle followed the busy routes used by the car and bus, the other went along an off- road route away from traffic. Sampling was conducted on two major routes in the city with relatively high peak traffic volumes. While the first route (journey one/J1) followed Main North Road in Redwood to the centre of town (Figure 4.3), the second route (journey two/J2) covered one of the busiest roads in Christchurch (Riccarton Road) to the centre of town (Figure 4.3). The off- road routes for the cycle measuring pollution exposures away from traffic traversed through Redwood Park for journey one (Figure 4.3) and through Hagley Park for journey two (Figure 4.3). In the mornings, the journey started from Redwood and ended at the University of Canterbury, while in the evenings the journey began at the University of Canterbury and ended on Main North Road. All four commuters left for the first journey at the same time and met at the centre of town before commencing on the second journey. The car driver spent approximately five minutes in a sheltered car park parking the car before and after the waiting period in town. Similarly, the bus commuter spent about five minutes at the bus stop while waiting to get on the bus to start the journey. This allowed the commuters to record sampling data in those micro-environments. Although all measures were taken to replicate the journeys across the modes; however this was not possible due to equipment failures. All morning journeys commenced at 7:45AM in the mornings and ended at approximately 09:00AM. The afternoon journeys began at 04:45PM and ended at approximately 06:00PM. These hours to chosen to cover the morning and evening peak travel times respectively. The table below summarises the total number of journeys made on each mode, specifying the number of trips done in the mornings and afternoons.

Mode	Morning (AM)	Afternoon (PM)	Total
Bus	32	20	52
Car	24	26	50
Off- road Bike	25	23	48
On- road Bike	27	24	51

Two fixed monitoring sites were established in Christchurch. Kestrels were mounted about 15 feet above ground in 341 Main North Road (Figure 4.4) and 69 Deans Avenue (Figure 4.4). While the Main North Road Kestrel provided information on wind speed, temperature and humidity for journey one, the Deans Avenue Kestrel was used to monitor weather conditions for journey two. The wind speed data was collected hourly, and the temperature and humidity measurements were collected every six seconds.

4.3.2 Auckland City

Fieldwork commenced in Auckland on 4 April 2009 and ended on 20 May 2009. The selected modes of transport were car, bus, bicycle and train. Sampling was conducted on one major route through the city with a relatively high peak traffic volume (Figure 4.5). In the mornings, the commute started at Mt. Albert and ended in Auckland Central Business District (ACBD), while in the evenings the journey took place from the Auckland CBD to Mt. Albert (Figure 4.4) All four commuters left for the journey at the same time. Sampling of air pollutants was carried out in an underground car park to assess exposure levels in such microenvironments. The car passenger spent approximately five minutes walking in the car park to collect sampling data. The bus and train commuters also spent a few minutes waiting at the outdoor bus station and walking through the underground metro station (Britomart) respectively. All morning journeys commenced at 7:45AM in the mornings and ended at approximately 09:00AM. The afternoon journeys began at 04:45PM and ended at approximately 06:00PM. These hours to chosen to cover the morning and evening peak travel times respectively. The table below summarises the total number of journeys made on each mode, specifying the number of trips done in the mornings and afternoons.

Mode	Morning (AM)	Afternoon (PM)	Total
Bus	14	10	24
Car	15	10	25
Bike	15	9	24
Train	15	10	25

The weather data for Auckland was derived from the NIWA Climate database in two meteorological weather stations. These weather stations were located in Henderson and Onehunga, and they provided information on wind speed, temperature and humidity.

4.4 Pre-fieldwork Preparation

Some preparatory work was carried before the start of the air pollution sampling. The GRIMM Dust Monitor was tested in a wind tunnel to determine how accurately it would able to measure particulate concentration under different conditions. Additionally, a dilution system was also developed for the TSI 3007 which permitted the condensation particle counter to operate within its maximum detectable concentration threshold, even when sampling extremely high particle concentrations.

4.4.1 Wind Tunnel Test

A wind tunnel test was carried out prior to the start of the air pollution sampling. The particulate sampler GRIMM Dust Monitor was tested to determine its ability to accurately measure the particulates at different wind speeds and with different orientation of the inlet tube. The samplers has relatively low volume pump, which is approximately 1.2 liters per minute and reports published by the National Institute for Water and Atmosphere (NIWA) show that these samplers are less effective with higher wind speeds when the inlet is pointing upwards, which is its normal position. The wind test was performed to determine if changing the position of the tube to face forward would make the measurements more accurate. This was done by placing a burning incense cone up- wind of the inlet tubes, and running a few tests at different wind speeds and orientations of the inlet. The wind tunnel test revealed that the samplers preformed at their optimum level at the speed of 50 kilometers per hour. The inlet tubes also needed to be facing forward instead of upwards for the instruments to be most effective.

4.4.2 Dilution System for the TSI 3007

The TSI model 3007 condensation particle counter is a hand-held device which uses isopropyl alcohol for measuring the concentration of submicron particulate matter in the air. Because the unit is lightweight and is powered by AA batteries, it can be taken into a variety of heavily polluted environments where its maximum detectable concentration is exceeded (Knibbs et al., 2007). This exceedences make the unit's output unreliable because of coincidence error; i.e., more than one particle enters the single- particle counting optics at any given time (Hameri et al., 2002). Although this can be corrected to some degree by applying a correction, the exceedence can potentially shorten the operational life of its alcohol wicks and filters (Westerdahl et al., 2005). To counter this problem, a pilot project (Knibbs et al., 2007) developed a simple and inexpensive dilution system which was effective at very high concentrations, capable of providing a dilution ratio of approximately 20:1. The results from the project showed that the dilution technique allowed the instrument to operate effectively at particle concentrations of up to ~8.5×10^5 p cm^{-3}, which is the highest concentration likely to be encountered in most sampling environments. The same dilution technique was used for this project.

4.5 Sampling Design

4.5.1 Inter-modal Comparison

The campaign methods were designed to assess the personal exposure of transport users in Christchurch City and Auckland City. The project monitored concentrations of the key traffic- related pollutants: particulates (those that are smaller than 10 microns, PM_{10}; those that are smaller than 2.5 microns, $PM_{2.5}$; and those smaller than 1 micron, $PM_{1.0}$; ultrafine particles, carbon monoxide (CO). All five measures of vehicle pollution were simultaneously measured whenever possible, and all samplers were co-located to ensure consistency. Although attempts were made to carry out the sampling under anti- cyclonic conditions, when wind speeds were light and pollution concentrations were expected to be at a maximum, this was not always possible. As a result, some of the sampling was carried out in windy conditions. All sampling took place at the same time every weekday, during expected peak traffic congestion- approximately before 8AM in the mornings and before 5PM in the evenings. Participants turned on the sampling equipments at the beginning of every journey and samplers were turned off at the end of every journey. The data collected on the routes on each mode of transport were downloaded daily for analysis. GPS data were also collected for each mobile sampler, and the commuters recorded any malfunction of the sampling equipments and vehicles. Additionally, they also identified and made note of particular high exposure events produced mainly by smokers or other non-traffic sources. The participants were asked not to smoke during the commuting periods.

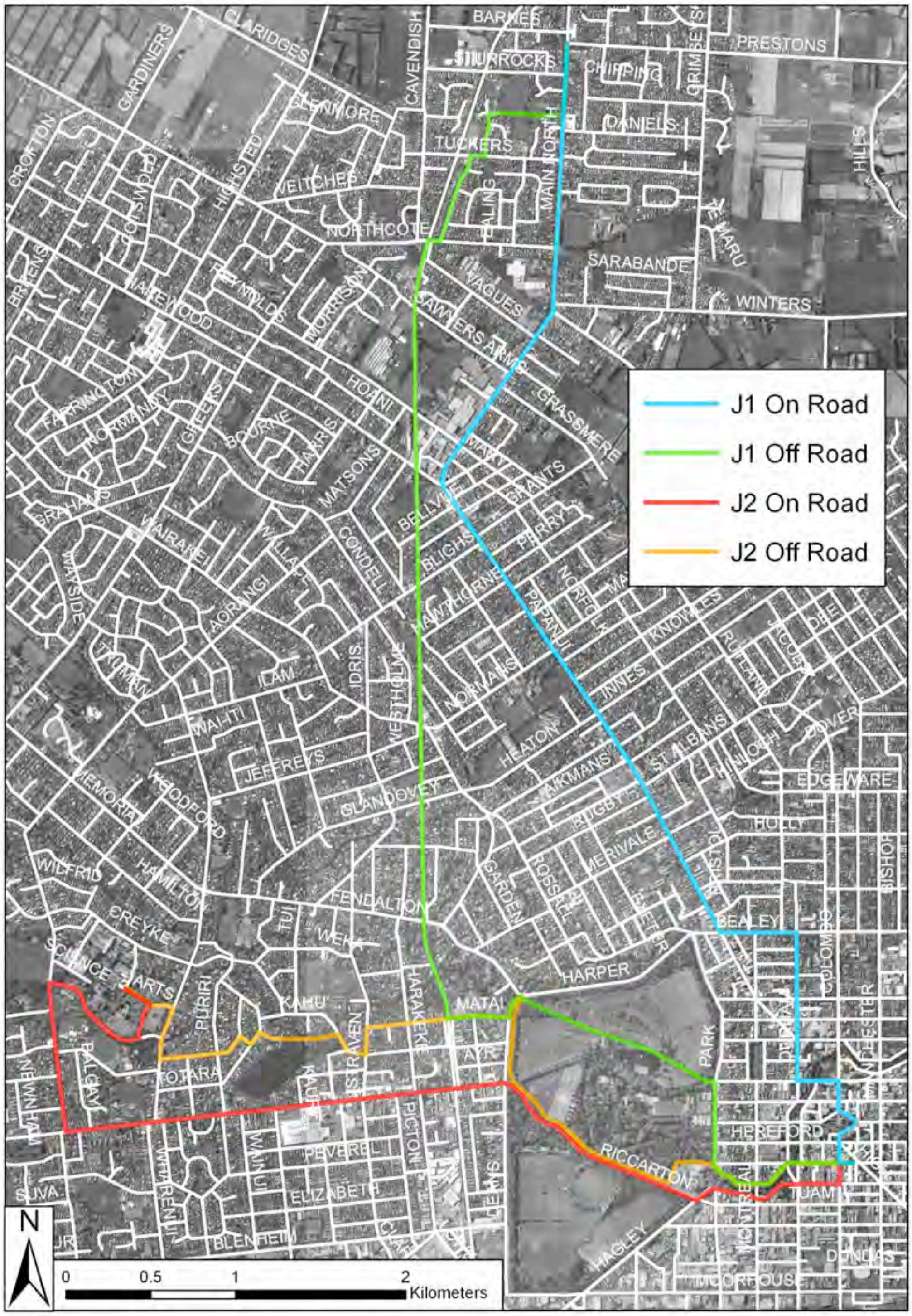


Figure 4.3 *Off-road and on-road routes for Christchurch*

Sourced from University of Canterbury aerial photo database

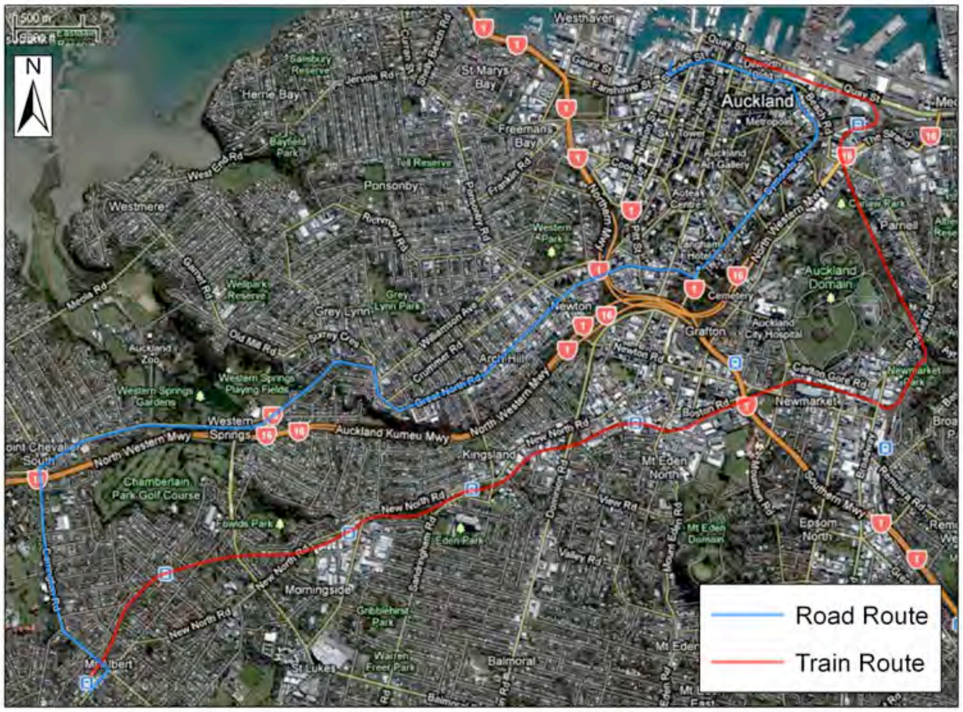


Figure 4.4 *Car and train route for Auckland*

Sourced from Google Map

4.5.2 Monitoring Exposures on Different Segments in a Journey

The purpose of this research was also to calculate the contribution of micro- scale activities to total personal pollution exposure while commuting in cars, trains and buses. This included the time spent throughout the entire journey from door to door and included activities such as walking through sheltered car- parks, waiting at bus stops and train stations. The aim was to identify peaks in pollution exposure on a commuter journey to relate them to isolated activities that potentially exacerbated personal exposure. To correctly execute this required several steps. Firstly, logging was carried out in the underground car parks for approximately ten minutes before the start of each journey in Christchurch and Auckland. Similarly, pollution data was also collected at bus stops and at Britomart, the underground train station in Auckland before the commute to measure exposure in these micro- spaces. Each journey was then divided into different segments or legs. The photographs taken with the Nokia N82 Mobile phone, which was fitted in every kit, was used to correctly identify and label the different segments in each journey. The segments included the actual journey (J), the time spent in the car park (CP), the time spent in an outdoor bus stop (S1) or an indoor bus stop (S2), time spent at the underground train station (TS), and finally, the waiting periods (W). There were three waiting periods- one before the journey started (W1), one in between the two journeys (W2) and one at the end of the journey (W3). There were two journeys in Christchurch, one between University of Canterbury and the centre of town (J2) along Riccarton Road and the second journey (J2) was a commute between the centre of town and Redwood along Papanui and Main North Roads. Each journey consisted of different segments. While first journey included the journey between Redwood and town W1, J1, C1, S1, W2, the second journey consisted of C2, J2, S2 and W3. The location of the segments and the weather stations in Christchurch are shown in Figure 4.5. The location of the segments in the Auckland journey are shown in Figure 4.6.

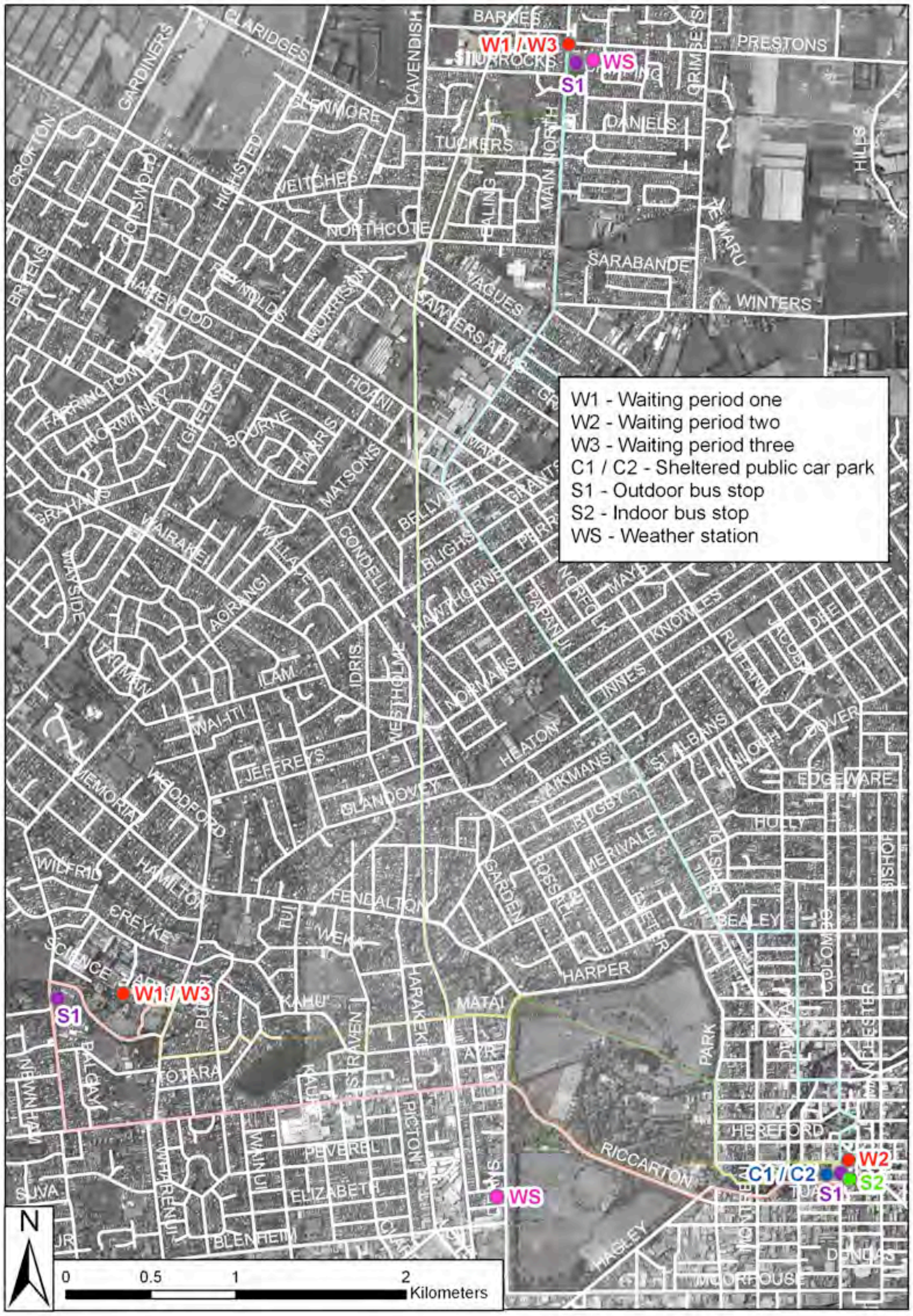


Figure 4.5 *Segments for journeys in Christchurch*

Sourced from University of Canterbury aerial photo database

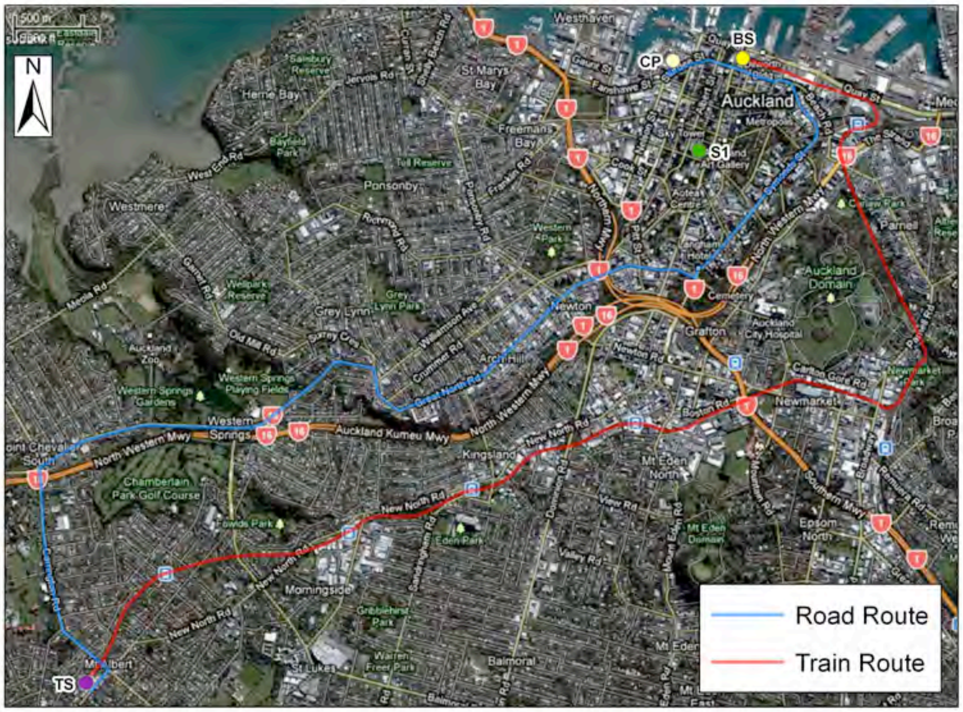


Figure 4.6 *Segments for journeys in Auckland*

Sourced from Google Map

4.6 Study Vehicles

4.6.1 Car

The model and make of the car used in the study was a Toyota Corolla. Manufactured in 1992, the car was a four-door sedan.

4.6.1.1 Car Characteristics

Before the start of the fieldwork, it was important to determine the air exchange rate (AER) of the vehicle. This was done by filling the car cabin with aerosol (incense), and then investigating the speed of decay of the particle concentration as the smoke was removed via leaks, filtration and deposition. The decay time is strongly related to the time it takes for polluted air from outside to penetrate into the vehicle. The following table shows typical values for AER (hour^{-1}) for cars.

Table 4.2 Typical values of AER ($hour^{-1}$)

Average car with vents open, windows closed	10- 100, increasing with speed
Average car with windows closed, recirculation on	<5
Average car with windows open	Few hundred, increasing with speed (vehicle and wind)

The experiment was conducted with the car vents open and windows closed, while traveling at a speed of 50km/hour. The GRIMM Dust Monitor was used to determine the speed of decay inside the car. The AER for the study vehicle was 2014 per day, and since the Excel default unit for time is day, the AER equalled 83.9 per hour. This value falls within the typical range for an average car.

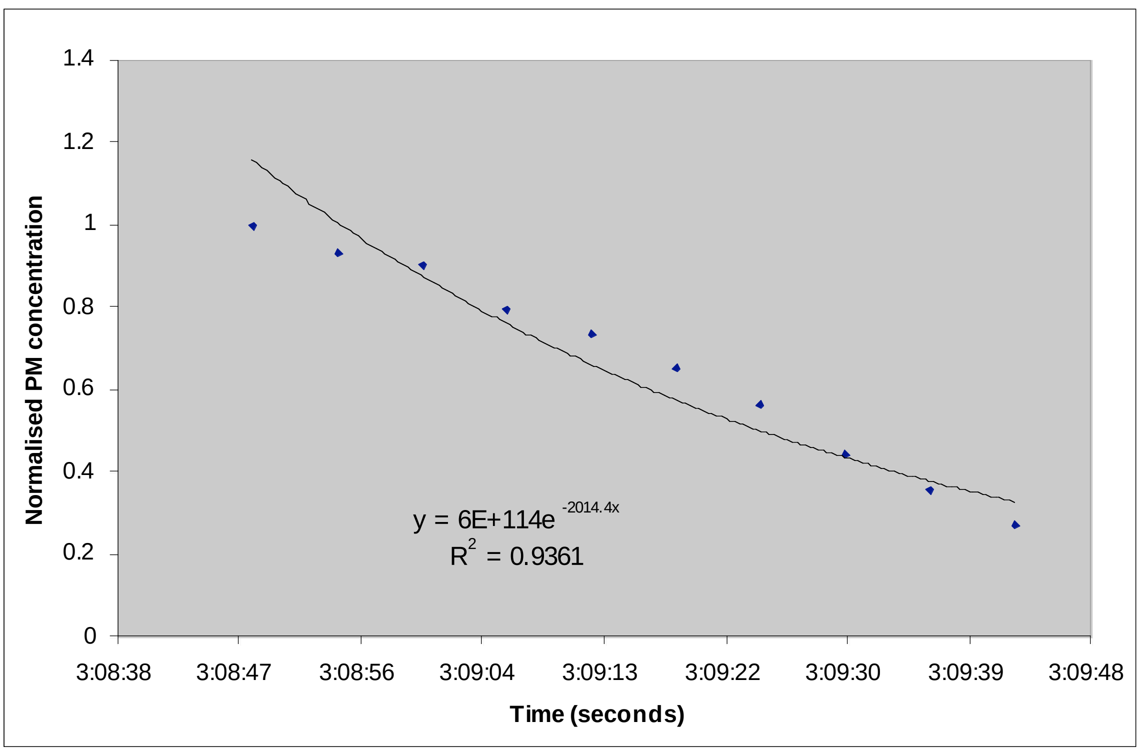


Figure 4.7 Exponential curve determining the AER of the study vehicle

4.6.1.2 Comparative Analysis

A comparative analysis was carried out to ensure that the study vehicle used was not a confounding factor that influenced pollution levels during the sampling. The second car used for this experiment was a 1993 four-door sedan. Two GRIMM Dust Monitors were placed in each car, and data was recorded as both cars were driven down Riccarton Road simultaneously for fifteen minutes on a busy afternoon. The same procedure was repeated on a quite stretch of country road. analysis showed that the two dust monitors corresponded relatively well with each other, thus ensuring that the study vehicle was not a confounding factor in the pollution study.

4.7 Quality Assurance and Quality Control

Before each commuting run, all equipments were time synced to match each other. This ensured that all the instruments followed the same time stamps. This was essential for correctly analysing the inter-modal data collected to isolate peaks in pollution exposure, and for identifying why these surges occurred. The batteries for the GRIMM Dust Monitors were charged and changed daily to ensure that the instruments remained fully functioning throughout the journey. The alcohol wick in the TSI 3007 was also changed frequently between commuting runs to allow it to function properly. The TSI 3007s were turned on at least ten minutes before the sampling took place. This allowed the instruments to 'warm up' before the actual data logging started.

4.8 Data Analysis

All descriptive computations and statistical analyses were made using a combination of three statistical packages. They included the Statistica software (version 8.0), the R Program (version2.9.2), and Stata 10. Descriptive analyses were done for all five pollutants measured on all four modes in each city. In addition, the descriptive statistics were also computed for the different segments of the journeys. ANOVA at 95% significance was used to compare the concentrations between different commuting modes, and between different legs of a journey. The post-hoc Bonferroni test was utlised to check the significance between the exposure means between the modes and the segments. T-tests were carried out to check the significance of the wind speed and the time of day. The exposure concentrations were highly skewed so the commuter data was log transformed. Logarithmic transformation of the raw data produced more normally distributed data, so all subsequent analyses were done using the log transformed data. Log-transformed data has been used in other pollution exposure studies in the past (Chertok et. al., 2004; Boogaard et al., 2009).

CHAPTER FIVE

Results: Christchurch

5.0 Introduction

The objective of this chapter is to present the results of the fieldwork carried out in Christchurch. While Section 5.1 will include results for the inter-modal comparison for the four modes- bus, car, cycle on road and cycle off road, Section 5.2 will demonstrate the results for the different segments of the car and bus journeys. Section 5.3 will include evidence of elevated exposures in individual journeys at the car parks and the indoor and outdoor bus stops. Section 5.4 will contain the results for other factors, which influence pollution exposure levels on commuter journeys. These include wind speed and the time of day. Sections 5.1 and 5.2 will include descriptive statistics and the results produced from ANOVA and the post-hoc Bonferroni test to determine any statistically significant difference between the different groups. Section 5.3 will include box and whisker plots showing elevated exposures in certain micro-environments in individual journeys. Section 5.4 will present results from the independent t-tests, which were carried out to ascertain the affect wind speed, and the time of day had on exposure levels.

The exposure concentrations distributions were highly skewed so the commuter exposure data was log transformed. Logarithmic transformation of the raw data produced more normally distributed data, so all subsequent analyses were done using the log-transformed data. Log- transformed data has been used in other pollution exposure studies in the past (Chertok et al., 2004; Gomez- Perales et al., 2007; Boogaard et al., 2009).

5.1 Inter-modal Comparisons

5.1.1 Carbon Monoxide (CO)

5.1.1.1 Descriptive Statistics

Table 5.1 *Inter-modal descriptive statistics for CO*

Mode	N	Mean	CI - 95%	CI 95%	Median	Min	Max	SD
Bus		3.07	3.05	3.09	2.77	1.00	10.88	1.11
Car		4.15	4.10	4.20	3.07	1.64	54.74	2.99
Bike Off		2.67	2.66	2.69	2.43	1.29	24.79	0.84
Bike On		2.96	2.94	2.97	2.50	1.44	27.94	1.28

Table 5.1 summarises the statistical results of CO levels in different transport modes. The CO level in a car is the highest with a mean average of 4.15 μg^3. This is followed by the bus, with the mean CO level of 3.07 μg^3. The cycling commuters had significantly lower levels of exposure compared with car and bus users, with the off- road cyclist being exposed to the lowest CO level. The inter-modal mean comparison for CO is presented in a box and whisker plots below (Figures 5.1 and 5.2). While Figure 5.1 shows the average concentration per trip, Figure 5.2 shows the average concentration for the total number of trips for each of the four modes. The width of the boxes is proportional to the time spent in each segment. The vertical extent of the boxes, which include the whiskers and the outliers, shows the overall distribution of the exposure data. The point in the middle represents the median.

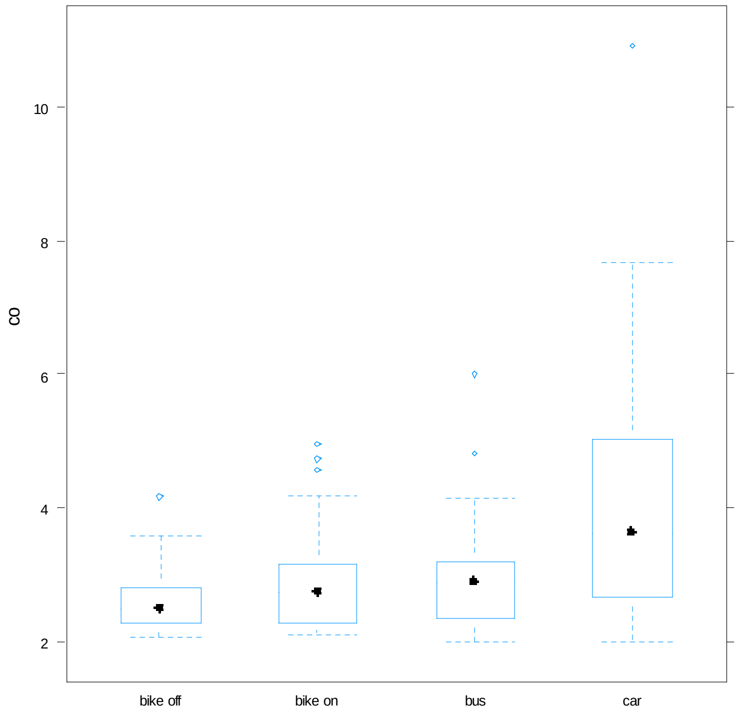


Figure 5.1 *Box and whisker plot showing the mean inter-modal CO exposures per trip*

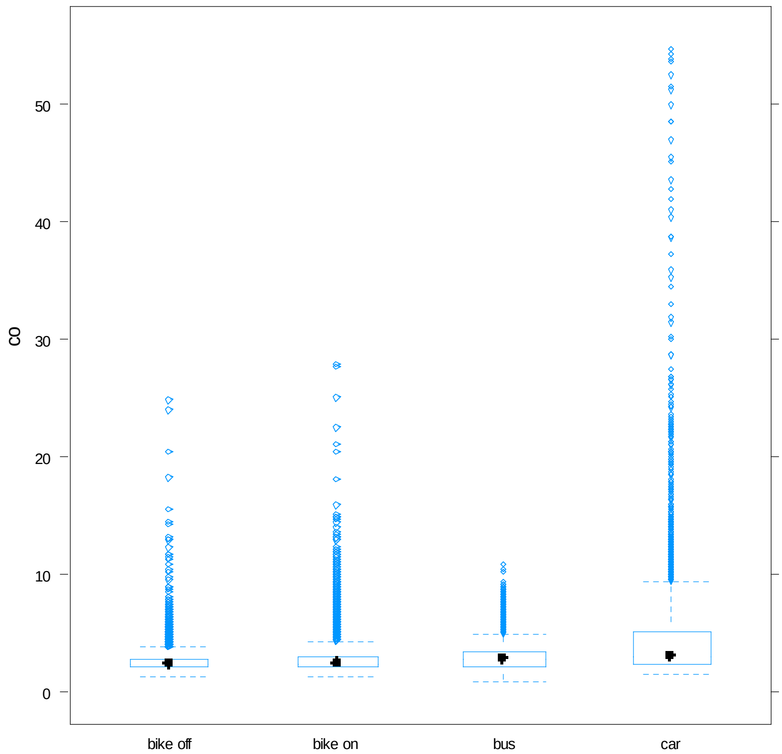


Figure 5.2 *Box and Whisker Plot showing the mean inter-modal CO exposure concentrations*

5.1.1.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.2 *Inter-modal analysis of variance for CO (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	907.87047	3	302.62349	2460.99	**<0.05**
Within groups	8365.04799	68026	0.12297		
Total	9272.92	68029	0.13631		

These results indicate that the overall model is statistically significant at p-value <0.05. This means that CO level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of <0.05. However, since the F test compared all the group means simultaneously it does not tell us where the differences lie. Thus, it is not possible to conclude that all four means are statistically different from each other. A post- hoc Bonferroni test was then carried out to locate the difference between each pair of means responsible for the overall significance. The result of the Bonferroni test is as follows (Table 5.3).

Table 5.3 *Bonferroni matrix for the effect of modal choice on CO exposure*

Row Mean **Col Mean**	**Bus** **3.07**	**Car** **4.15**	**Bike Off** **2.67**
Car **4.15**	**1.08** **p <0.05**		
Bike Off **2.67**	**-1.03** **p <0.05**	**-1.48** **p<0.05**	
Bike On **2.96**	**-0.11** **p<0.05**	**-1.19** **p<0.05**	**0.29** **p <0.05**

As Table 5.3 illustrates, the Bonferroni test yields significant differences between all group means at p<0.05. The CO level for car was significantly higher than it was for bus; the CO level for bus was higher than for bike off- road and bike on- road. Similarly, the CO level in the car was also greater than both bike off- road and bike on- road. As for the cyclists, the CO exposure was higher for the on-road cyclists than it was for the off-road one.

5.1.2 PM_{10}

5.1.2.1 Descriptive Statistics

Table 5.4 *Inter-modal descriptive statistics for PM_{10}*

Mode	N	Mean	CI - 95.000%	CI 95.000%	Median	Min	Max	SD
Bus		43.26	42.46	44.06	34.40	7.00	1437.60	48.56
Car		36.74	35.94	37.53	30.80	10.80	515.80	30.21
Bike Off		40.10	39.58	40.62	33.50	4.30	573.50	33.27
Bike On		32.46	32.23	32.70	30.17	8.42	110.80	12.55

Concerning PM_{10} exposure, the bus commuter was exposed to the highest level of PM_{10} with a mean exposure level of 43.26 μg^3. This was 1.17 times higher than for the car user (36.74 μg^3), 1.07 times higher than the off- road cyclist (40.10 μg^3) and 1.33 times higher than the on- road cyclist (32.46 μg^3). While Figure 5.3 shows the average PM_{10} per trip concentration for each mode, Figure 5.4 illustrates the overall average concentration for the different modes.

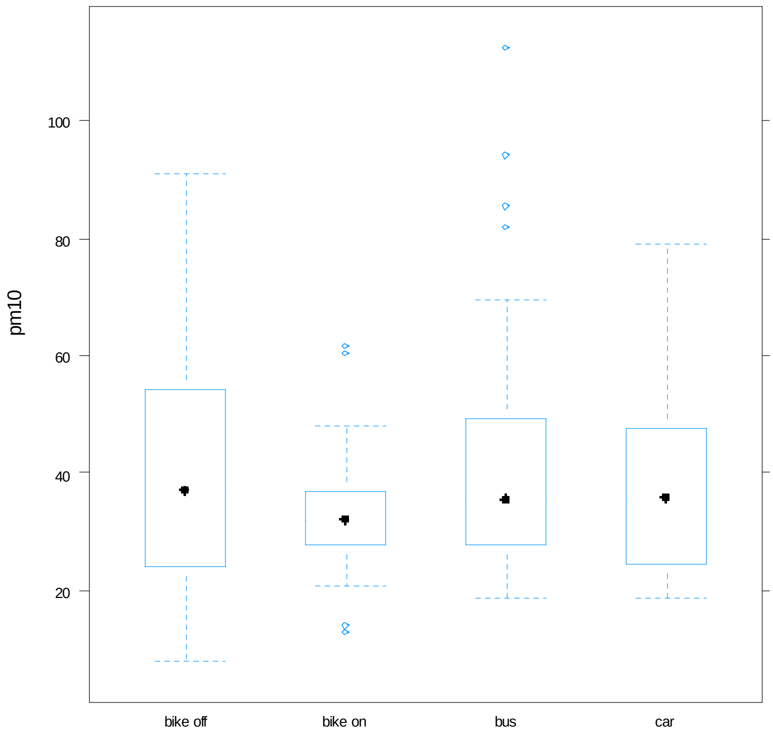


Figure 5.4 *Box and whisker plot showing the mean inter- modal PM_{10} exposure per trip*

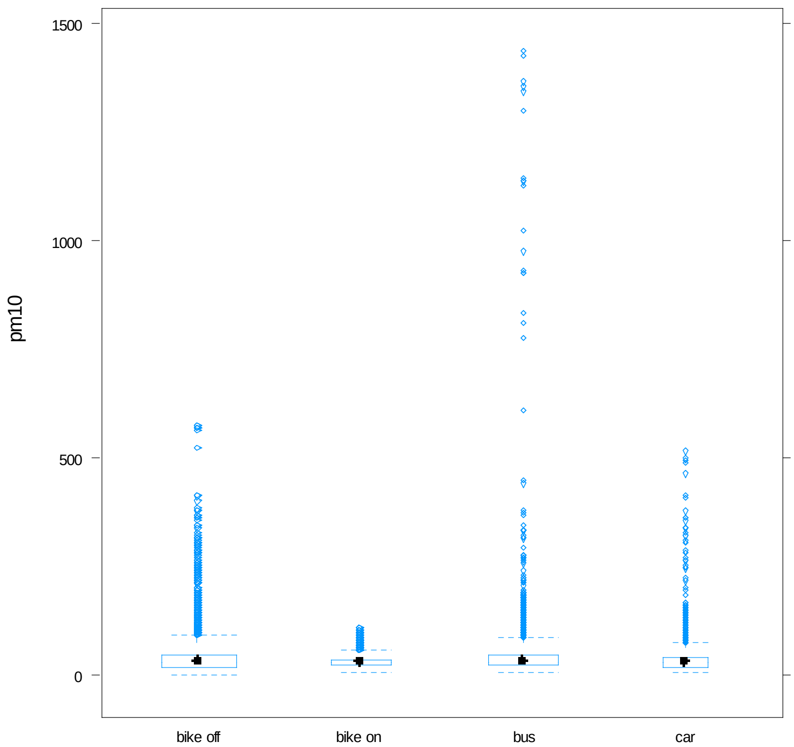


Figure 5.4 *Box and whisker plot showing the mean inter- modal PM_{10} exposure concentrations*

5.1.2.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.5 *Inter-modal analysis of variance for PM_{10} (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	220.884636	3	73.6282119	236.37	**<0.05**
Within groups	14414.559	46276	0.311491032		
Total	14635.4436	46279	0.316243731		

These results show that the overall model is statistically significant at p value <0.05. This means that PM_{10} level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is computed in the table below (Table 5.6).

Table 5.6 *Bonferroni matrix for the effect of modal choice on PM_{10} exposure*

Row Mean Row Col	**Bus 43.26**	**Car 36.74**	**Bike Off 40.10**
Car 36.74	**-6.52 p<0.05**		
Bike Off 40.10	**-3.16 p<0.05**	3.36 p= 0.292	
Bike On 32.46	**-13.96 p<0.05**	**-4.28 p<0.05**	**-7.64 p <0.05**

The Bonferroni test (Table 5.6) shows that the all group means are statistically significantly different from each other except in the case of the comparison between the car and off road cycle- exposure. The pollutant exposure was higher for the bus commuter than it was for the car user or cyclists. The car driver was also exposed to higher levels of PM_{10} than the on-road cyclist. While examining the exposure comparisons between the cyclists, off-road cyclist was exposed to significantly higher PM_{10} rates than the on- road cyclist.

5.1.3 $PM_{2.5}$

5.1.3.1 Descriptive Statistics

Table 5.7 *Inter-modal descriptive statistics for $PM_{2.5}$*

Mode	N	Mean	CI - 95%	CI 95%	Median	Min	Max	SD
Bus		22.88	22.57	23.20	19.40	5.00	268.00	19.20
Car		17.13	16.89	17.37	13.40	4.00	76.50	9.02
Bike Off		20.21	19.93	20.48	16.80	1.30	505.40	17.67
Bike On		17.14	16.99	17.28	15.30	3.74	61.50	7.73

As with $PM_{10,}$ the exposure for $PM_{2.5}$ was the highest for the bus user. The commuter who travelled by cycle off the road had a significantly lower exposure at 20.21 $\mu g^{3.}$ This was significantly higher than the exposure level for on-road cyclist whose mean exposure was 17.14 μg^3. The car driver experienced the lowest $PM_{2.5}$ exposure, which was 17.13 µg3. Figures 5.5 and 5.6 show box and whisker plots of average concentration per trip and total average concentration across modes respectively.

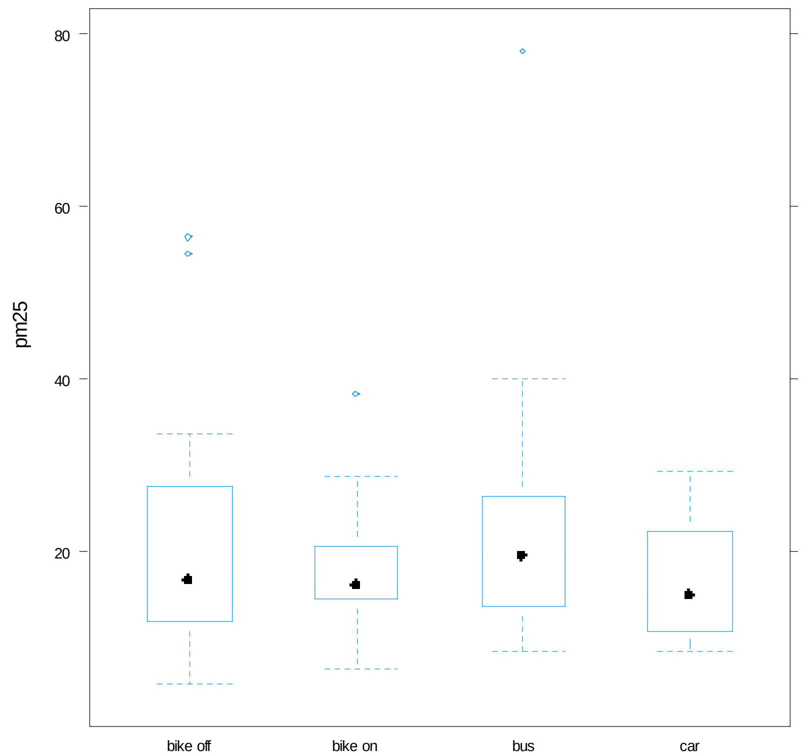


Figure 5.5 *Box and whisker plot showing the mean inter-modal $PM_{2.5}$ exposures per trip*

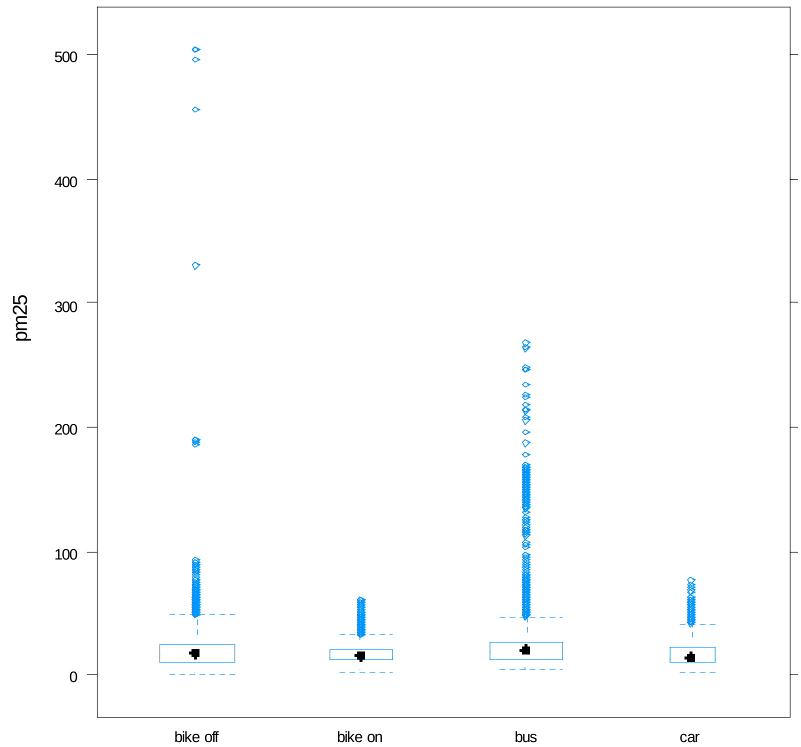


Figure 5.6 *Box and Whisker Plot showing the mean inter- modal $PM_{2.5}$ exposure concentrations*

5.1.3.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.8 *Inter-modal analysis of variance for PM_{10} (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	426.3503	3	142.1168	446.67	**<0.05**
Within groups	14723.46	46276	0.318166		
Total	15149.81	46279	0.327358		

These results show that the overall model is statistically significant at p level <0.05. This means that the $PM_{2.5}$ level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.9).

Table 5.*9 Bonferroni matrix for the effect of modal choice on $PM_{2.5}$ exposure*

Row Mean Row Mean	Bus 22.88	Car 17.13	Bike Off 20.21
Car 17.13	**-5.75 p<0.05**		
Bike Off 20.21	**-2.67 p <0.05**	**3.08 p <0.05**	
Bike On 17.14	**-5.74 p<0.05**	**0.01 p <0.05**	**-3.07 p <0.05**

As displayed by Table 9, the Bonferroni test yields significant differences between all group means at p<0.05. The pollutant exposure for the bus user was higher than the level experienced by the car driver or the cyclists. The car commuter had a lower $PM_{2.5}$ level than both the cyclists did, although the difference in exposure between the car and the on-road cyclist is very marginal (0.01 μg^3). Lastly, the exposure was significantly lower for the on- road cyclist than it was for the off- road cyclist.

5.1.4 PM_1

5.1.4.1 Descriptive Statistics

Table 5.10 *Inter-modal descriptive statistics for PM_1*

Mode	N	Mean	CI - 95%	CI 95%	Median	Min	Max	SD
Bus		12.98	12.78	13.18	10.40	2.40	118.60	12.03
Car		9.43	9.27	9.60	7.00	1.90	55.90	6.32
Bike Off		8.82	8.66	8.97	6.30	0.30	312.30	0.77
Bike On		9.53	9.40	9.66	7.50	0.92	51.70	6.80

When examining PM_1 exposure across the four modes, Table 5.10 shows that the personal exposure for the pollutant was significantly higher for the bus commuter compared to the car user and the cyclists. The bus commuter was exposed to rates of PM_1 1.38 times higher than the car driver, 1.47 times higher than the off-road cyclist and 1.36 times higher than the on- road cyclist (Figures 5.7 and 5.8).

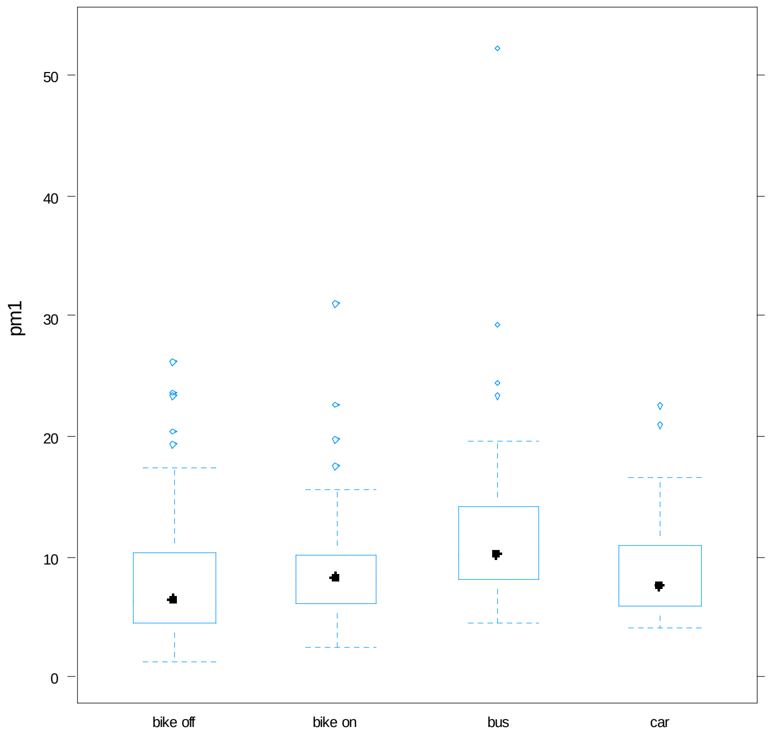


Figure 5.7 *Box and whisker plot showing the mean inter- modal* PM_1 *exposure per trip*

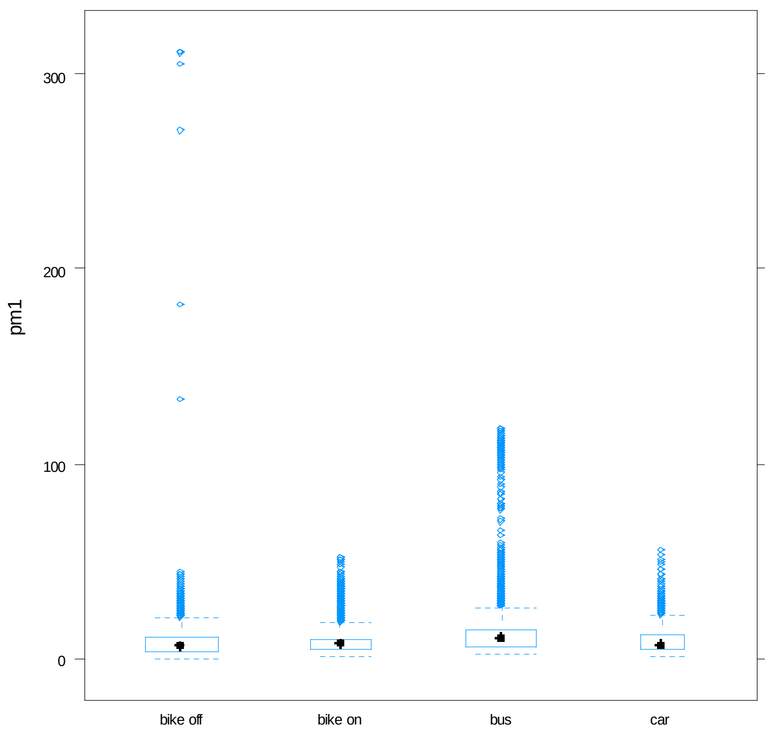


Figure 5.8 *Box and whisker plot showing the mean inter- modal* PM_1 *exposure concentrations*

5.4.1.3 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.11 *Inter-modal analysis of variance for PM_1 (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	1645.05446	3	548.3515	1225.35	**<0.05**
Within groups	20708.7645	46276	0.447505		
Total	22353.8189	46279	0.483023		

These results show that the overall model is statistically significant at p level <0.05. The PM_1 level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.12).

Table 5.12 *Bonferroni matrix for the effect of modal choice on PM_1 exposure*

Row Mean **Col Mean**	**Bus** **12.98**	**Car** **9.43**	**Bike Off** **8.82**
Car **9.43**	**-3.55** **p<0.05**		
Bike Off **8.82**	**-4.16** **p <0.05**	**-0.61** **p <0.05**	
Bike On **9.53**	**-3.45** **p <0.05**	-0.10 p= 1	**0.71** **p <0.05**

Table 5.12 shows that the Bonferroni test yields significant differences between all group means at p<0.05 except between the car and on-road cyclist. The pollutant exposure for the bus user was higher for PM_1 compared to the car driver and the cyclists. The car commuter had higher a PM_1 level than the off-road cyclist. Lastly, the exposure was significantly lower for the off- road cyclist than it was for the on- road cyclist.

5.1.5 UFP

5.1.5.1 Descriptive Statistics

Table 5.13 *Inter- modal descriptive statistics for UFP*

Mode	N	Mean	CI - 95%	CI 95%	Median	Min	Max	SD
Bus		74332	72141	76524	52973	0	1213963	70736
Car		56123	54884	57363	30816	251	1060014	74011
Bike Off		22721	22067	23375	11753	0	741752	35912
Bike On		38897	37906	39888	18436	0	1304048	61335

When examining UFP exposure across the four modes, Table 5.13 shows that the personal exposure for the pollutant was highest for the bus commuter and lowest for off-road cyclist. The UFP exposure for on- road cyclists was lower than for car users. Figures 5.9 and 5.10 show box and whisker plots of average UFP concentration per trip and total average concentration across modes respectively.

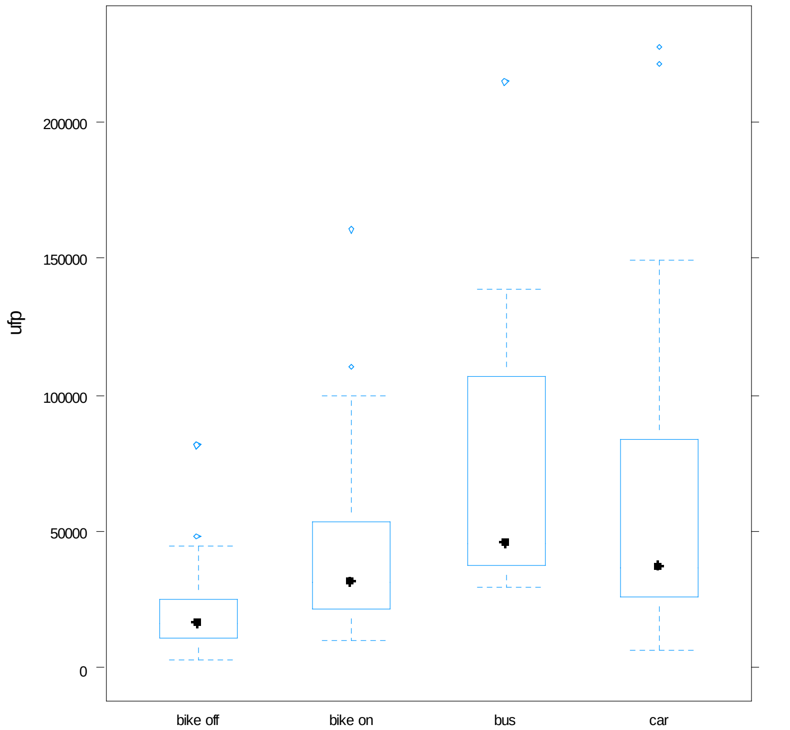


Figure 5.9 *Box and whisker plot showing the mean inter- modal UFP exposure per trip*

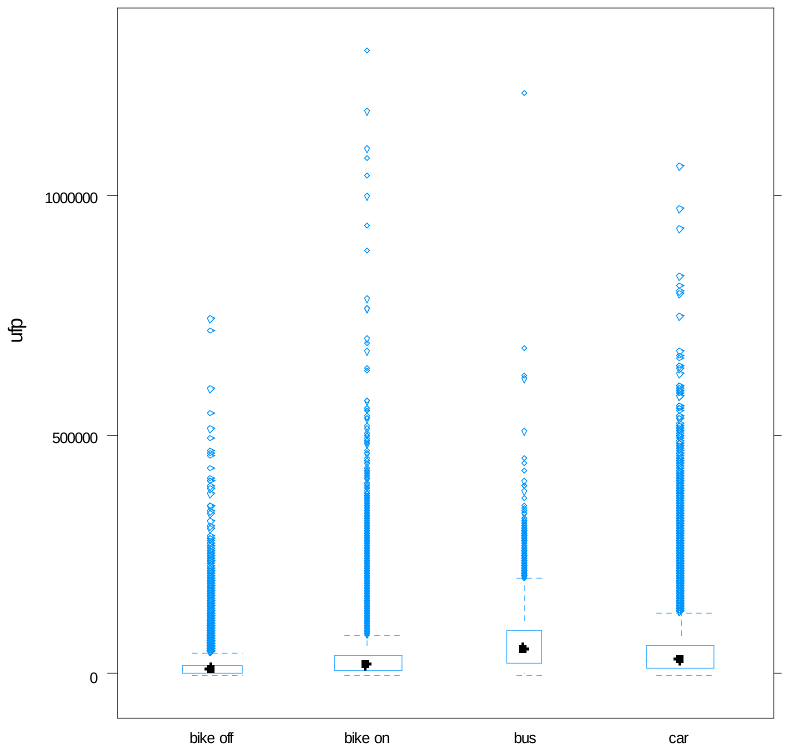


Figure 5.10 *Box and whisker plot showing the mean inter- modal UFP exposure concentrations*

5.1.5.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.14 *Inter-modal analysis of variance for PM_1 (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	7093.67701	3	2364.559	2470.18	**<0.05**
Within groups	41819.9434	43688	0.957241		
Total	48913.6205	43691	1.119535		

Table 5.14 displays that the overall model is statistically significant at p level <0.05. This means that the UFP level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of 0.05. The statistical significance between each of the group means is shown in the Bonferroni table below (Table 5.15).

Table 5.15 *Bonferroni matrix for the effect of modal choice on UFP exposure*

Row Mean Col Mean	**Bus 74332**	**Car 56123**	**Bike Off 22721**
Car 56123	**-18209 p <0.05**		
Bike Off 22721	**-51611 p<0.05**	**-33402 p<0.05**	
Bike On 38897	**-35435 p<0.05**	**-17226 p<0.05**	**422867 p <0.05**

Table 5.15 displays that the Bonferroni test yields significant differences between all group means at p<05. The pollutant exposure for the bus user was higher than the levels experienced by the car driver and the cyclists. The car commute had higher $PM_{2.5}$ levels than both the cyclists did. Lastly, the exposure was significantly lower for the off-road cyclist than it was for the on-road cyclist.

5.1.6 Summary

To summarise the pollution exposure for inter-modal comparison, the bus was the most polluting mode of transport for all three types particulate matters and UFPs. The car journey had the highest CO exposure, compared to the other three modes. The off- road cyclist was exposed to the lowest level of CO, PM_1 and UFPs, while the on- road cyclist had the lowest exposure to PM_{10} and $PM_{2.5}$ particulates.

5.2 Segment Comparison for Bus and Car Journeys

This section will divided into two sub-sections containing results for the segment comparisons for the bus (Section 5.2.1) and car (Section 5.2.2) journeys. The bus journey was divided into seven different segments[1]. They are as follows:

- W1: Waiting period before the start of the journey
- W2: Waiting period between the first and the second journey at the centre of town
- W3: Waiting period after the end of the journey
- J1: Trip made from Redwood Park to the centre of town down Main North Road
- J2: Trip made from the centre of town to the University of Canterbury down Riccarton Road
- S1: Waiting period at the outdoor bus stop
- S2: Waiting period at the indoor bus station

Similarly, the car journey was also divided into seven segments. They were:

- W1: Waiting period before the start of the journey
- W2: Waiting period between the first and the second journey at the centre of town
- W3: Waiting period after the end of the journey
- J1: Trip made from Redwood Park to the centre of town down Main North Road
- J2: Trip made from the centre of town to the University of Canterbury down Riccarton Road
- C1: Time spent in the sheltered car park in the city after J1
- C2: Time spent in the sheltered car park in the city before J2

Each sub-section will consist of the descriptive statistics for every segment. The averages will also be displayed graphically in a box and whisker plot. ANOVA results and the post- hoc Bonferroni test to determine the statistically significant difference between the different segments will also be included.

[1] Since all journeys across the modes had the same starting (W1), mid-(W2) and end point (W3), W1, W2 and W3 are common to both the bus and car journeys.

5.2.1 Bus Journey

5.2.1.1 CO

5.2.1.1.1 Descriptive Statistics

Table 5.16 *Descriptive statistics for carbon monoxide for bus segments*

Mode	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	4.11	3.94	4.28	3.21	1.50	8.88	1.82	2.96
J1	3.08	3.05	3.11	2.69	1.60	10.88	1.15	25.85
S1	3.27	3.21	3.32	2.91	1.29	8.67	1.24	5.79
W2	2.82	2.79	2.85	2.55	1.88	6.84	0.92	11.04
S2	2.55	2.50	2.60	2.40	1.60	5.98	0.48	3.79
J2	3.14	3.11	3.17	2.91	1.09	10.31	1.06	18.53
W3	2.80	2.77	2.83	2.79	1.00	6.13	0.60	9.27

Table 5.16 shows that the CO exposure was highest during the waiting period at the start of the journey. This was followed by the exposure in the outdoor bus stop. Journey two down Riccarton Road had a higher level of CO than journey one from Main North Road. The waiting periods between the two journeys and at the end experienced higher levels of CO exposure than the time spent at the indoor bus station.

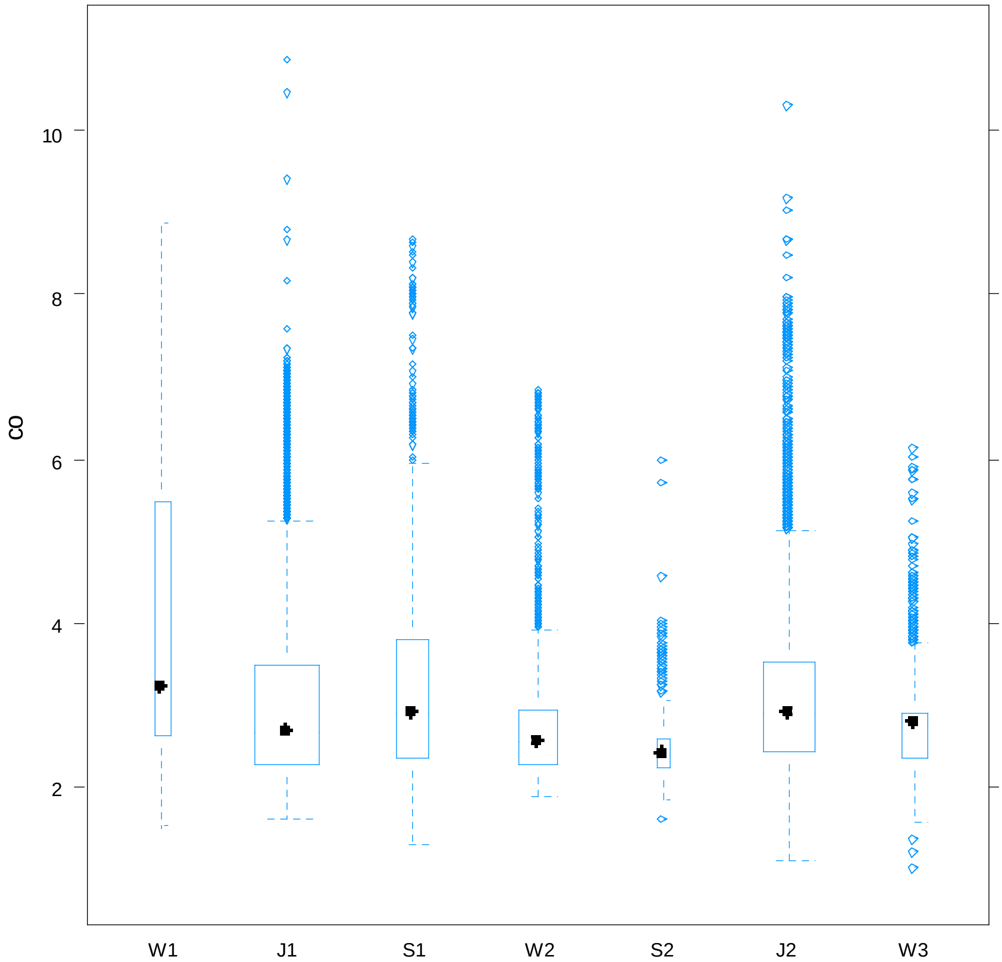


Figure 5.11 *Box and whisker plot showing the mean CO exposure for bus segments*

The box and whisker plot above (Figure 5.11) represents the exposure for CO for each of the segments in the bus journey. The width of the boxes is proportional to the time spent in each segment. The vertical extent of the boxes, which include the whiskers and the outliers, shows the overall distribution of the exposure data. The point in the middle represents the median.

5.2.1.1.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.17 *Inter-segment analysis of variance for CO (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	65.43744	6	10.9062399	122.79	**<0.05**
Within groups	1640.487	18469	0.08882379		
Total	1705.924	18475	0.09233689		

These results (Table 5.17) show that the overall model is statistically significant at p level <0.05. This means that the CO level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of 0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.18).

Table 5.18 *Bonferroni matrix for the effect of bus segments on CO exposure*

Row Mean **Col Mean**	**J1** **3.08**	**J2** **3.14**	**S1** **3.27**	**S2** **2.55**	**W1** **4.11**	**W2** **2.82**
J2 **3.14**	**0.06** **p<0.05**					
S1 **3.27**	**0.19** **p<0.05**	**0.13** **p<0.05**				
S2 **2.55**	**-0.53** **p<0.05**	**-0.59** **p<0.05**	**-0.72** **p<0.05**			
W1 **4.11**	**1.03** **p<0.05**	**0.97** **p<0.05**	**0.84** **p<0.05**	**1.56** **p<0.05**		
W2 **2.82**	**-0.26** **p<0.05**	**-0.32** **p<0.05**	**-0.45** **p<0.05**	**0.27** **p<0.05**	**-1.29** **p<0.05**	
W3 **2.80**	**-0.28** **p<0.05**	**-0.32** **p<0.05**	**-0.47** **p<0.05**	**0.25** **p<0.05**	**-01.31** **p<0.05**	-0.02 p=1

As displayed by Table 5.18, the Bonferroni test yields significant differences between all group means at $p<0.05$ except between the two waiting periods, W2 and W3.

5.2.1.2 PM_{10}

5.2.1.2.1 Descriptive Statistics

Table 5.19 *Descriptive statistics for PM_{10} for bus segments*

Mode	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	40.13	37.88	42.37	35.00	11.60	258.40	24.93	2.96
J1	44.94	44.11	45.76	35.60	11.40	192.80	29.88	25.85
S1	38.40	37.07	39.73	30.80	7.00	276.00	27.64	5.79
W2	43.81	39.70	47.92	28.10	9.40	1437.60	95.04	11.04
S2	43.90	41.82	45.98	41.30	15.80	102.60	19.38	3.79
J2	42.32	41.67	42.97	37.80	11.00	176.60	20.77	18.53
W3	48.54	40.72	56.35	33.40	11.60	1138.80	102.13	9.27

While examining PM_{10} exposures, the final waiting period had the highest exposure to PM_{10}. This was followed by J1, the bus journey from Redwood Park to the city, which had a higher exposure than the second journey down Riccarton Road from the centre of town. The indoor bus stop had a higher level of PM_{10} than the outdoor bus stop or the remaining waiting periods. Figure 5.12 displays the PM_{10} levels for each of the segments in sequential order.

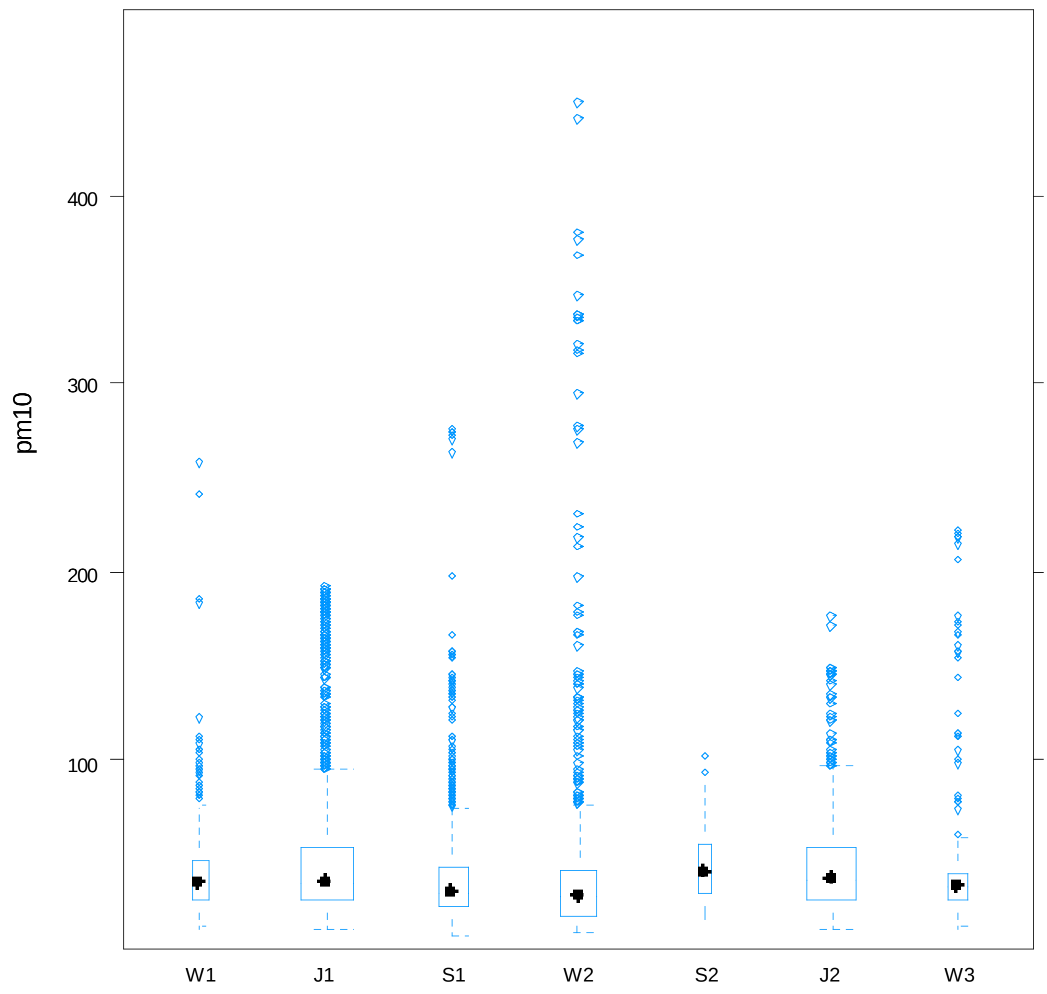


Figure 5.12 *Box and whisker plot showing the mean PM_{10} exposure for bus segments*

5.2.1.1.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.20 *Inter-segment analysis of variance for PM_{10} (logged value)*

Source	**SS**	**Df**	**MS**	**F**	**Prob >F**
Between Groups	115.4412	6	19.2402	67.02	<0.05
Within groups	4081.352	14216	0.287096		
Total	4196.793	14222	0.295092		

These results (Table 5.20) show that the overall model is statistically significant at p level <0.05. This means that the PM_{10} level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.21).

Table 5.21 *Bonferroni matrix for the effect of bus segments on PM_{10} exposure*

Row Mean **Col Mean**	**J1** **44.94**	**J2** **42.32**	**S1** **38.40**	**S2** **43.90**	**W1** **40.13**	**W2** **43.81**
J2 **42.32**	-2.62 p=0.974					
S1 **38.40**	**-6.54** **p<0.05**	**-3.92** **p<0.05**				
S2 **43.90**	1.04 p=1	1.58 p=0.959	**5.50** **p<0.05**			
W1 **40.13**	**-4.81** **p=0.03**	**-2.19** **p=.0.216**	**1.73** **p=0.068**	**-3.77** **p=0.077**		
W2 **43.81**	**-1.13** **p<0.05**	**1.49** **p<0.05**	**5.41** **p<0.05**	**-0.09** **p<0.05**	**3.68** **p<0.05**	
W3 **48.54**	**3.6** **p<0.05**	**6.22** **p=<0.005**	**10.14** **p=0.169**	**-4.64** **p=0.008**	8.41 p=1	**4.73** **p<0.05**

Table 5.21 displays the Bonferroni test results between the group means. No statistical difference was found between the two journeys or between journeys one and the indoor bus stop. Similarly, no statistical difference resulted between the first waiting period and journey one or the indoor and outdoor bus stops. The difference in the pollutant level was also not significant between the final waiting period and the outdoor bus stop or the first waiting period before the start of the journey.

5.2.1.3 $PM_{2.5}$

5.2.1.3.1 Descriptive Statistics

Table 5.22 *Descriptive Statistics for $PM_{2.5}$ for Bus Segments*

Mode	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	21.02	20.31	21.73	20.20	5.60	48.80	7.90	2.96
J1	25.30	24.62	25.99	19.60	7.40	170.00	24.90	25.85
S1	20.78	20.30	21.26	19.40	7.00	54.00	10.04	5.79
W2	21.11	20.16	22.06	17.20	5.40	234.80	21.90	11.04
S2	20.19	19.11	21.27	16.30	8.80	55.00	10.04	3.79
J2	22.27	21.96	22.58	19.80	5.20	73.40	10.04	18.53
W3	21.55	19.60	23.50	20.40	5.00	268.00	25.51	9.27

The two journeys had the highest exposure to $PM_{2.5}$ levels compared to the other segments, with J1 having a significantly higher $PM_{2.5}$ level than J2. All three waiting periods during the journey had higher $PM_{2.5}$ levels than both types of bus stops. While just examining exposure levels in the bus stops, the outdoor bus stop was shown to be the more polluting micro-environment of the two. The box and whisker plot below (Figure 5.13) displays the $PM_{2.5}$ levels for each of the segment in sequential order.

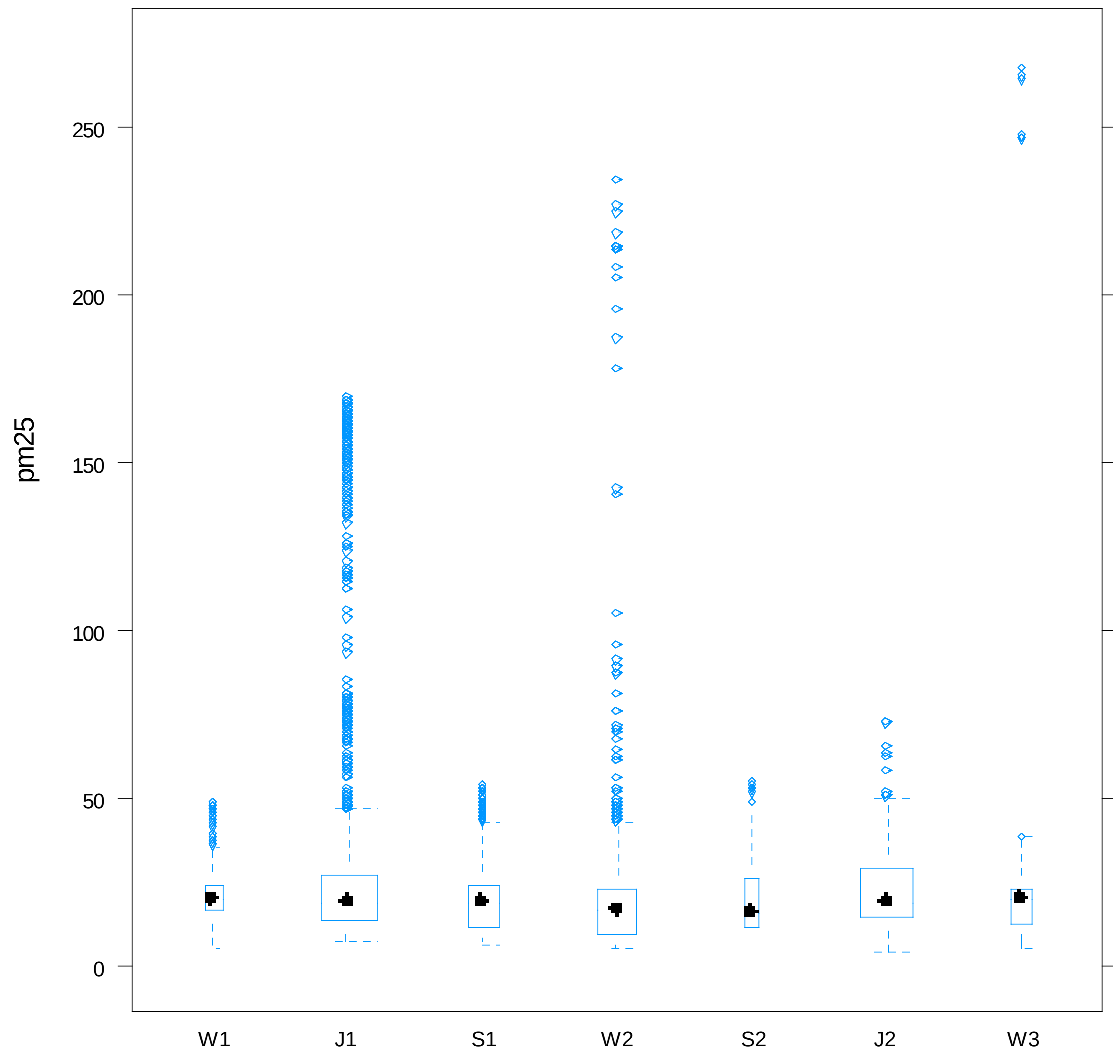


Figure 5.13 *Box and whisker plot showing the mean $PM_{2.5}$ exposure for bus segments*

5.2.1.3.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.23 *Inter-segment analysis of variance for $PM_{2.5}$ (logged value)*

Source	**SS**	**Df**	**MS**	**F**	**Prob >F**
Between Groups	60.6406514	6	10.1067752	35.74	**<0.05**
Within groups	4019.9112	14216	0.28277372		
Total	4080.55185	14222	0.286918285		

These results (Table 5.23) show that the overall model is statistically significant at p level <0.05. This means that the $PM_{2.5}$ level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of 0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.24).

Table 5.24 *Bonferroni matrix for the effect of bus segments on $PM_{2.5}$ exposure*

Row Mean –Col Mean (log)	**J1 25.30**	**J2 22.27**	**S1 20.78**	**S2 20.19**	**W1 21.02**	**W2 21.11**
J2 22.27	-3.03 p=1					
S1 20.78	**-4.52 p<0.05**	**-1.49 p<0.05**				
S2 20.19	**-5.11 p=0.002**	**-2.08 p=0.01**	**-0.59 p<0.05**			
W1 21.02	-4.28 p=0.985	-1.25 p=1	0.24 p=0.648	0.83 p=0.475		
W2 21.11	**-4.19 p<0.05**	**-1.16 p<0.05**	**0.33 p<0.05**	0.92 p=0.711	**0.09 p<0.05**	
W3 21.55	**-1.95 p<0.05**	**-0.72 p<0.05**	0.77 p=0.515	1.36 p=1	**0.53 p=0.018**	0.44 p=0.957

Table 5.24 displays the Bonferroni test results between the group means. No statistical difference was found between the two journeys. Similarly, no statistical difference resulted between the first waiting period and any of the other segments. The difference in pollutant level was also not significant between the final waiting period and the two types of bus stops or the final waiting period at the end of the journey.

5.2.1.4 PM_1

5.2.1.4.1 Descriptive Statistics

Table 5.25 *Descriptive statistics for PM_1 for bus segments*

Mode	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	11.01	10.33	11.69	8.20	3.20	41.60	7.57	2.96
J1	15.67	15.19	16.16	11.40	3.40	118.60	17.60	25.85
S1	11.02	10.71	11.34	9.80	3.00	42.80	6.53	5.79
W2	10.32	10.04	10.60	8.60	3.20	52.20	6.54	11.04
S2	14.40	13.51	15.30	12.20	5.40	48.40	8.31	3.79
J2	12.44	12.23	12.66	10.60	2.60	54.40	6.89	18.53
W3	9.47	9.05	9.88	8.40	2.40	44.40	5.46	9.27

For PM_1 exposures, journey one down Main North Road proved to be the most polluting environment. The PM_1 level in the indoor bus stop exceeded the levels present in the outdoor bus stop, journey two and all the waiting periods. The box and whisker plot below (Figure 5.14) displays the PM_1 levels for each of the segment in sequential order.

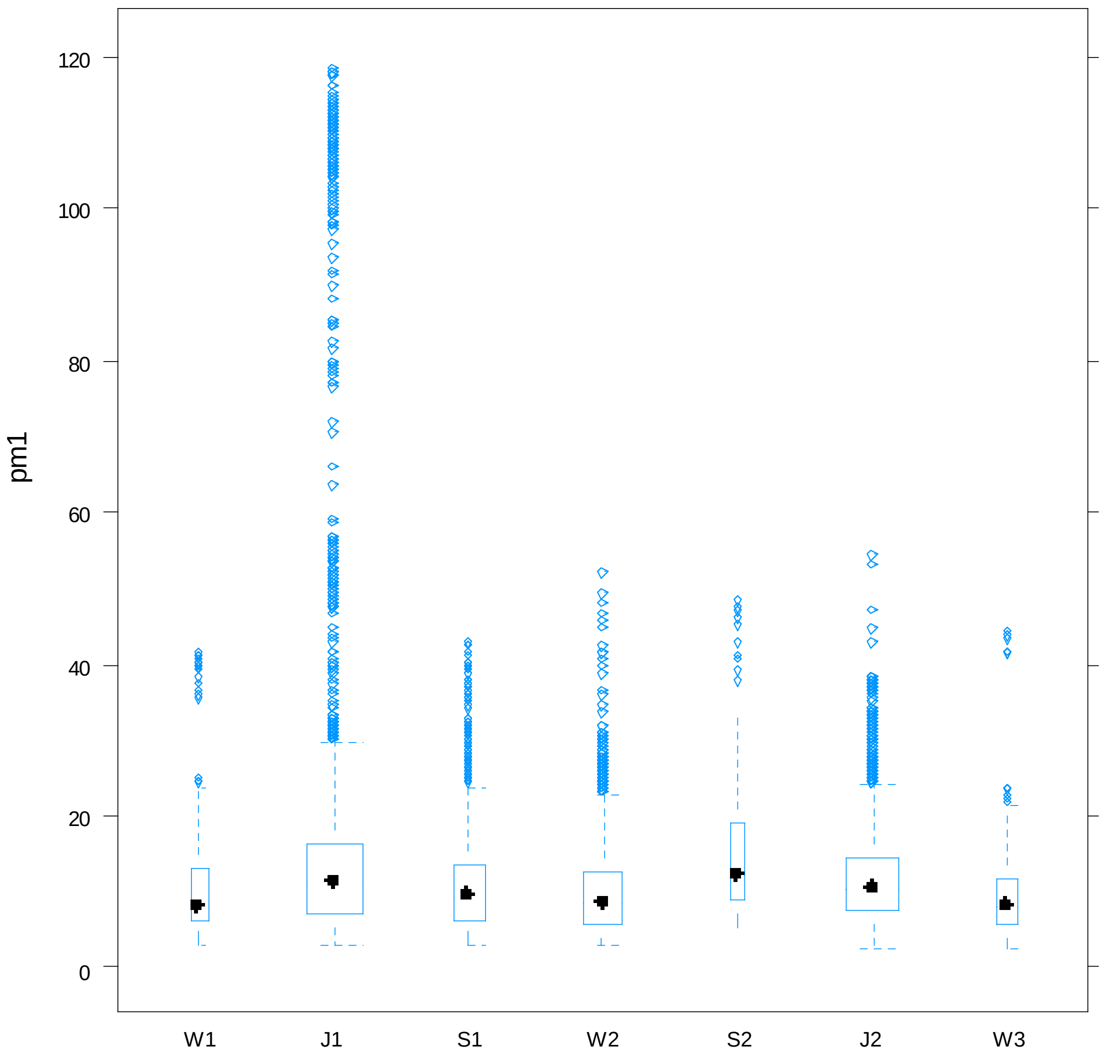


Figure 5.14 *Box and whisker plot showing the mean PM_1 exposure for bus segments*

5.2.1.4.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.26 *Inter-segment analysis of variance for PM_1 (logged value)*

Source	**SS**	**Df**	**MS**	**F**	**Prob >F**
Between Groups	225.577414	6	37.5962356	112.01	**<0.05**
Within groups	4771.61961	14216	0.335651351		
Total	4997.19702	14222	0.351370906		

These results (Table 5.26) show that the overall model is statistically significant at p level <0.05. This means that the PM_1 level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.27).

Table 5.27 *Bonferroni matrix for the effect of bus segments on PM_1 Exposure*

Row Mean –Col Mean (log)	**J1 15.67**	**J2 12.44**	**S1 11.02**	**S2 14.40**	**W1 11.01**	**W2 10.32**
J2 12.44	**-3.23 p<0.05**					
S1 11.02	**4.65 p<0.05**	**-1.42 p<0.05**				
S2 14.40	-1.27 p=0.901	**1.96 p=0.001**	**3.38 p<0.05**			
W1 11.01	**-4.66 p<0.05**	**-1.43 p<0.05**	-0.01 p=0.999	**-3.39 p<0.05**		
W2 10.32	**-5.35 p<0.05**	**-2.12 p<0.05**	**-0.7 p<0.05**	**-4.08 p<0.05**	-0.69 p=0.799	
W3 9.47	**-6.2 p<0.05**	**-2.97 p<0.05**	**-1.55 p<0.05**	**-4.93 p<0.05**	**-1.54 p=0.013**	-0.85 p=0.192

No statistical significance was found between the first journey and the indoor bus stop at the level p<0.05. Similarly, the differences between the first waiting period and the outdoor bus stop or the second waiting period were also not significant.

5.2.1.4 UFP

5.2.1.4.1 Descriptive Statistics

Table 5.28 *Descriptive statistics for UFP for bus segments*

Mode	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	144041	127316	160766	120282	43520	616623	82103	2.96
J1	60511	58907	62116	58807	10032	173610	32346	25.85
S1	43997	37454	50539	21590	3235	403987	59953	5.79
W2	30710	28455	32966	20539	0	321833	28835	11.04
S2	102864	90551	115177	91095	25372	352780	64241	3.79
J2	116380	111482	121278	90003	10008	506990	85103	18.53
W3	77682	50286	105079	27400	0	1213963	152849	9.27

In terms of UFP exposures, the first waiting period at the beginning of the journey had the most ultrafine particle count at 144041. This was followed by J2 at 116380 particles. The indoor bus stop; however, was more polluting than the remaining segments. The final waiting period had higher UFP levels than both the outdoor bus stop and the second waiting period, which was the cleanest micro- environment in terms of UFP exposure. The box and whisker plot below (Figure 5.15) displays the UFP levels for each of the segment in sequential order.

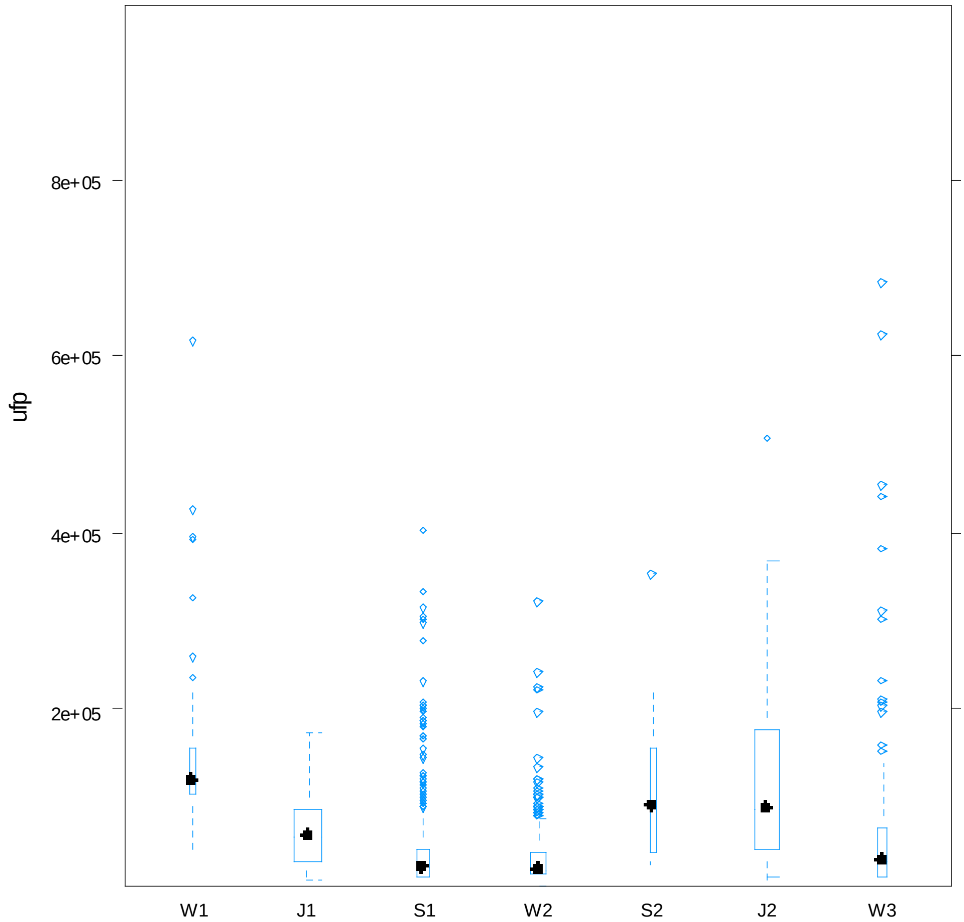


Figure 5.15 *Box and whisker plot showing the mean UFP exposure for bus segments*

5.2.1.5.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.29 *Inter-segment analysis of variance for UFP (logged value)*

Source	SS	df	MS	F	Prob >F
Between Groups	920.004338	6	153.334056	259.72	**<0.05**
Within groups	2368.02059	4011	0.590381599		
Total	3288.02493	4017	0.818527491		

These results (Table 5.29) show that the overall model is statistically significant at p level <0.05. This means that the UFP level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.30).

Table 5.30 *Bonferroni matrix for the effect of bus segments on UFP exposure*

Row Mean –Col Mean (log)	J1 60511	J2 116380	S1 43997	S2 102864	W1 144041	W2 30710
J2 116380	**55869 p<0.05**					
S1 43997	**-16514 p<0.05**	**72383 p<0.05**				
S2 102864	**42353 p<0.05**	-13516 p=1	**58867 p<0.05**			
W1 144041	**83530 p<0.05**	**27661 p<0.05**	**100044 p<0.05**	**41177 p=0.001**		
W2 30710	**-29801 p<0.05**	**-85670 p<0.05**	-13287 p=1	**-72154 p<0.05**	**-113,331 p<0.05**	
W3 77682	**17171 p=0.008**	**-38698 p<0.05**	**33685 p<0.05**	**-25182 p<0.05**	**-66359 p<0.05**	**42972 p<0.05**

As displayed by Table 5.30, the Bonferroni test yields significant differences between all group means at $p<0.05$ except between the second journey and the indoor bus stop or between the outdoor bus stop and the waiting period in town.

5.2.1.6 Summary

Although less than six minutes were spent at the outdoor bus stop, the CO exposure in that micro-environment exceeded the exposures on both journeys which lasted more than eighteen minutes. Similarly, the indoor bus stop had a significantly higher level of UFP exposure when compared to the bus journey down Main North Road even though the time waiting for a bus was less than four minutes. While examining the pollution level comparisons between the indoor and outdoor bus stops, the indoor bus stop had significantly higher levels of PM_1 and UFP exposures than the outdoor bus stop.

5.2.2 Car Journey

5.2.2.1 CO

5.2.2.1.1 Descriptive Statistics

Table 5.31 *Descriptive statistics for CO for car segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	4.05	3.85	4.26	3.60	1.98	8.35	1.66	1.89
J1	5.35	5.24	5.46	4.96	1.64	54.36	3.82	19.03
C1	5.25	5.06	5.45	4.07	2.18	16.52	3.01	3.54
W2	2.76	2.73	2.78	2.50	1.70	14.54	0.96	22.42
C2	4.95	4.54	5.35	2.53	2.02	54.74	6.08	3.47
J2	4.28	4.21	4.35	3.64	1.92	14.88	2.26	16.02
W3	3.86	3.62	4.10	3.40	2.18	5.50	1.32	4.03

The CO exposures were higher during the time spent at the car parks before and after the first journey compared to all the other segments except for the first journey. The maximum level of exposure was the highest at the C2 at 54.74 μg^3. The waiting periods during the journey had the lowest CO exposures. The box and whisker plot below (Figure 5.16) displays the CO levels for each of the segment in sequential order.

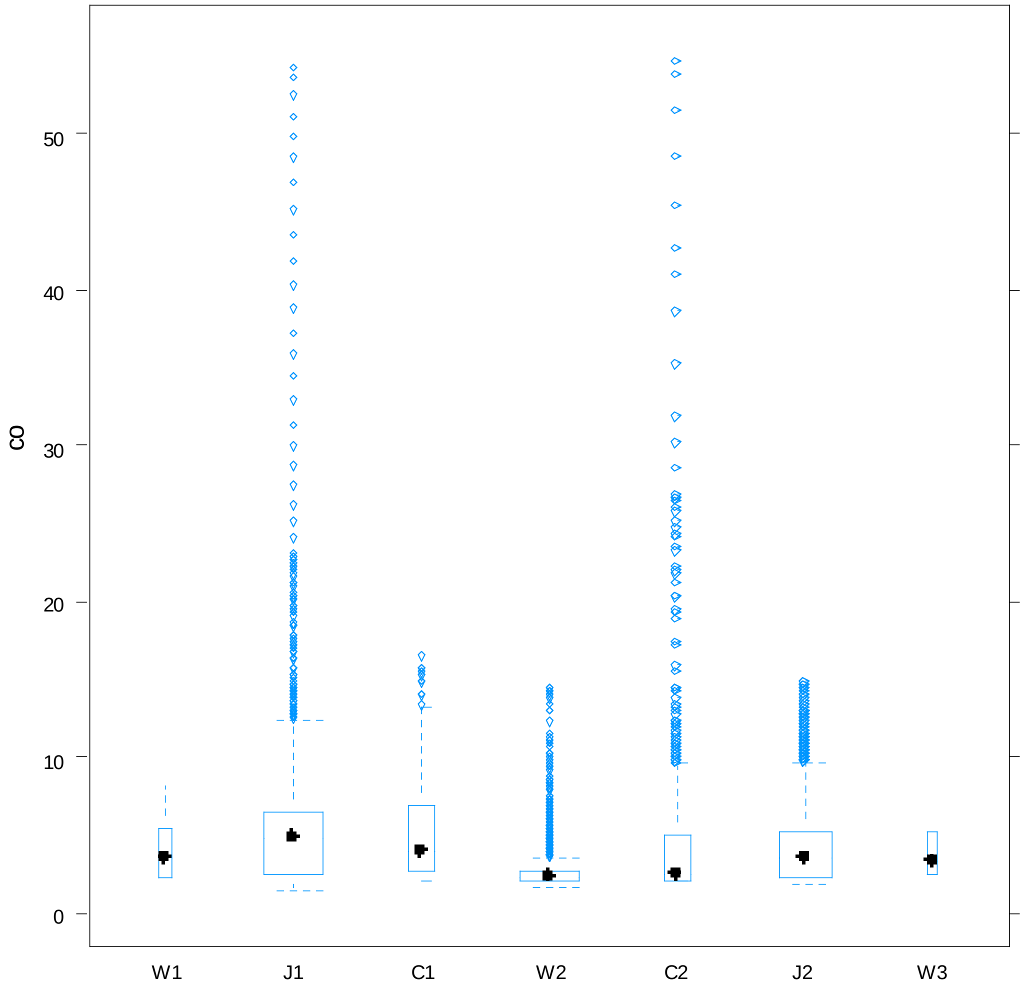


Figure 5.16 *Box and whisker plot showing the CO exposure for car segments*

5.2.2.1.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.32 *Inter-segment analysis of variance for CO (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	1149.32467	6	191.5541	652.18	**<0.05**
Within groups	4798.10381	16336	0.293713505		
Total	5947.42848	16342	0.363935166		

These results (Table 5.32) indicate that the overall model is statistically significant at p level <0.05. This means that the CO level for at least one of segments of the car journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.33).

Table 5.33 *Bonferroni matrix for the effect of car segments on CO exposure*

Row Mean –Col Mean	**C1 5.25**	**C2 4.95**	**J1 5.35**	**J2 4.28**	**W1 4.05**	**W2 2.76**
C2 4.95	**-0.30 p<0.05**					
J1 5.35	0.10 p=1	**0.40 p<0.05**				
J2 4.28	**-0.97 p<0.05**	**-0.67 p<0.05**	**-1.07 p<0.05**			
W1 4.05	**-1.20 p<0.05**	-0.90 p=1	**-1.30 p<0.05**	-0.23 p=1		
W2 2.76	**-2.49 p<0.05**	**-2.19 p<0.05**	**-2.59 p<0.05**	**-1.52 p<0.05**	**-1.29 p<0.05**	
W3 3.86	**-1.39 p<0.05**	-1.09 p=1	**-1.49 p<0.05**	-0.42 p=1	-0.19 p=1	**1.1 p<0.05**

The Bonferroni test yields significant differences between all group means at p<0.05 except between J1 and C1. In addition, neither C2 nor J2 obtained statistically significant results when compared to the first and third waiting periods. The CO exposures experienced during the first waiting period and the final waiting period were also not seen to be significant.

5.2.2.2 PM_{10}

5.2.2.2.1 Descriptive Statistics

Table 5.34 *Descriptive statistics for PM_{10} car segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	31.42	27.31	35.52	29.80	21.00	49.60	8.52	1.89
J1	28.48	27.98	28.98	25.60	11.90	62.70	10.48	19.03
C1	45.22	43.43	47.00	45.10	20.90	82.50	14.76	3.54
W2	48.71	46.57	50.84	40.20	13.10	515.80	46.43	22.42
C2	43.22	41.25	45.20	37.95	21.60	100.00	15.94	3.47
J2	29.25	28.45	30.05	26.05	10.80	94.80	15.46	16.02
W3	24.62	23.76	25.48	24.20	18.20	31.70	3.56	4.03

The highest PM_{10} level was experienced during the waiting period at the centre of town. The exposures in the car parks before and after journey one exceeded the particulate exposures in other the other segments. The waiting period at end of the journey was seen to be the least polluting micro-environment in terms of PM_{10} exposure. The second journey had a slightly higher level of PM_{10} than journey one. The box and whisker plot below (Figure 5.17) displays the PM_{10} levels for each of the segment in sequential order.

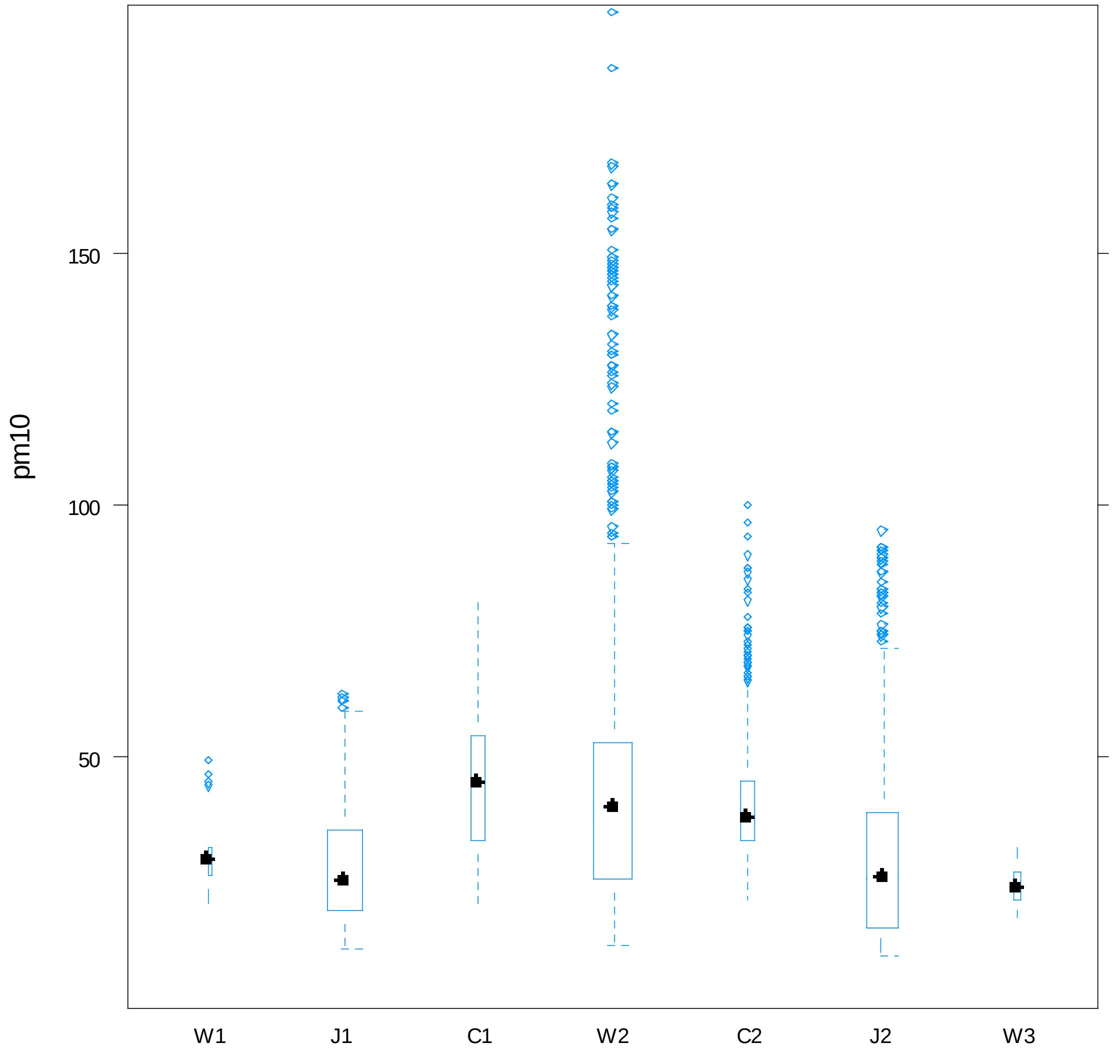


Figure 5.17 *Box and whisker plot showing the PM_{10} exposure for car segments*

5.2.2.2.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.35 *Inter-segment analysis of variance for PM_{10} (logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	250.410349	6	41.7350582	191.45	**<0.05**
Within groups	1208.99234	5546	0.217993571		
Total	1459.40269	5552	0.262860716		

Table 5.35 shows that the overall model is statistically significant at p level <0.05. This means that the level of PM_{10} for at least one of segments of the car journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.36).

Table 5.36 *Bonferroni matrix for the effect of car segments on PM_{10} exposure*

Row Mean –Col Mean (log)	**C1 45.22**	**C2 43.22**	**J1 28.48**	**J2 29.25**	**W1 31.42**	**W2 48.71**
C2 43.22	-2.00 p=0.998					
J1 28.48	**-16.74 p<0.05**	**-14.74 p<0.05**				
J2 29.25	**-15.97 p<0.05**	**-13.97 p<0.05**	0.77 p=0.679			
W1 31.42	**-13.80 p=0.044**	-11.80 p=0.156	2.94 p=0.995	2.17 p=0.942		
W2 48.71	3.49 p=0.342	5.49 p=1	**20.23 p<0.05**	**19.46 p<0.05**	17.29 p=0.232	
W3 24.62	**-2.06 p<0.05**	**-18.60 p<0.05**	-3.86 p=0.925	-4.63 p=1	-6.8 p=0.761	**-24.09 p<0.05**

This post- hoc test results show that the PM_{10} level in the car park was statistically significantly different from both of the journeys. However, the car park levels were not shown to be significantly related to the waiting period at the centre of town. The difference in the PM_{10} levels between the journeys and the W1 and W3 were also not seen to be significant.

5.2.2.3 $PM_{2.5}$

5.2.2.3.1 Descriptive Statistics

Table 5.37 *Descriptive statistics for $PM_{2.5}$ car segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	8.04	6.69	9.38	6.70	6.30	13.70	2.79	1.89
J1	15.42	15.08	15.77	12.30	6.60	37.70	7.17	19.03
C1	20.63	19.83	21.42	21.00	9.90	34.90	6.61	3.54
W2	20.07	19.58	20.56	18.50	6.70	76.50	10.59	22.42
C2	19.31	18.38	20.23	18.95	8.40	41.40	7.46	3.47
J2	14.92	14.50	15.35	11.30	4.00	62.80	8.20	16.02
W3	8.61	8.34	8.89	8.90	6.40	10.40	1.14	4.03

The $PM_{2.5}$ level was highest in the car park after journey one. The second highest level was experienced at the centre of town during the waiting period. The time spent at the car park after the waiting period at the centre of town had a higher $PM_{2.5}$ level compared to the remaining segments. J1 had a slightly higher exposure level than J2. The lowest $PM_{2.5}$ level was found in the waiting period at the beginning of the journey. The box and whisker plot below (Figure 5.18) displays the $PM_{2.5}$ levels for each of the segments in sequential order.

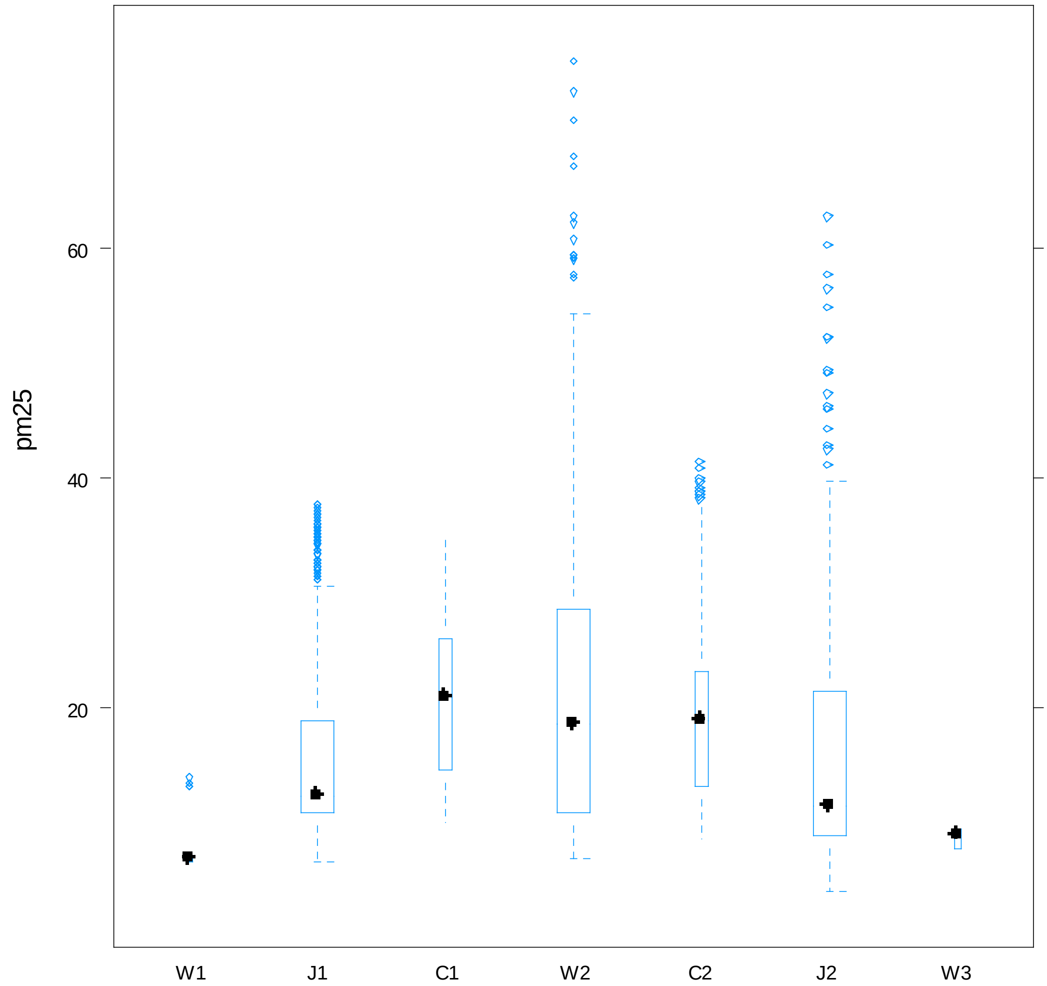


Figure 5.18 *Box and whisker plot showing the $PM_{2.5}$ exposure for car segments*

5.2.2.3.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.38 *Inter-segment analysis of variance for $PM_{2.5}$ (logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	137.445204	6	22.907534	101.12	<0.05
Within groups	1256.44045	5546	0.226548946		
Total	1393.88566	5552	0.251060097		

As can be seen from Table 5.38, the overall model is statistically significant at p level <0.05. This means that the level of $PM_{2.5}$ for at least one of segments of the car journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.39).

Table 5.39 *Bonferroni matrix for the effect of car segments on $PM_{2.5}$ exposure*

Row Mean –Col Mean (log)	**C1 20.63**	**C2 19.31**	**J1 15.42**	**J2 14.92**	**W1 8.04**	**W2 20.07**
C2 19.31	-1.32 p=0.664					
J1 15.42	**-5.21 p<0.05**	**-3.89 p<0.05**				
J2 14.92	**-5.71 p<0.05**	**-4.39 p<0.05**	**-0.50 p<0.05**			
W1 8.04	**-12.59 p<0.05**	**-11.27 p<0.05**	**-7.38 p<0.05**	**-6.88 p<0.05**		
W2 20.07	-0.56 p=0.009	0.76 p=1	**4.65 p<0.05**	**5.15 p<0.05**	**12.03 p<0.05**	
W3 8.61	**-12.02 p<0.05**	**-10.7 p<0.05**	**-6.81 p<0.05**	**-6.31 p<0.05**	0.57 p=1	**-11.46 p<0.05**

Table 5.39 indicates that the $PM_{2.5}$ levels had significant differences between all group means at $p<0.05$ except between C1 and C2, between W2 and C1 and between W1 and W3.

5.2.2.4 PM_1

5.2.2.4.1 Descriptive Statistics

Table 5.40 *Descriptive statistics for PM_1 for car segments*

Segment	Mean	CI -95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	2.78	2.20	3.37	2.20	2.10	5.20	1.22	1.89
J1	8.98	8.73	9.22	6.50	3.10	32.00	5.13	19.03
C1	12.36	11.73	12.99	11.10	5.10	26.60	5.19	3.54
W2	9.90	9.58	10.22	7.00	2.60	30.80	6.98	22.42
C2	12.35	11.51	13.19	11.85	4.50	35.10	6.77	3.47
J2	8.72	8.38	9.05	6.60	1.90	55.90	6.50	16.02
W3	2.97	2.93	3.01	2.90	2.70	3.40	0.18	4.03

Table 5.40 displays the results for the PM_1 exposures in the different segments of the car journey. The PM_1 exposure was highest in the car park. The waiting period in town between the journeys proved to more polluting than both the journeys in terms of PM_1 levels. Journey one was more polluting than journey two. The first waiting period at the start of the journey was the least polluting micro-environment. The box and whisker plot below (Figure 5.19) displays the PM_1 levels for each of the segment in sequential order.

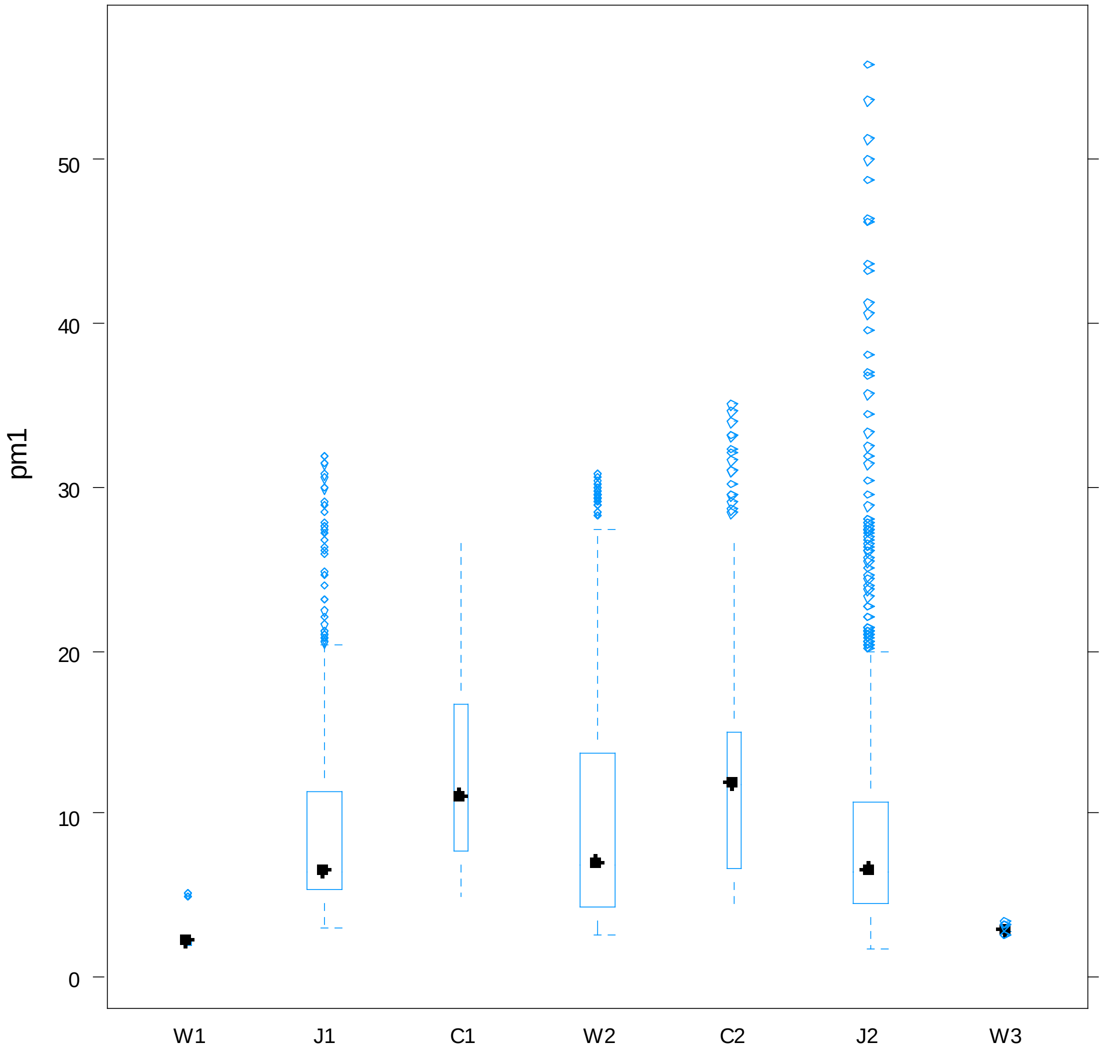


Figure 5.19 *Box and whisker plot showing the PM_1 exposure for car segments*

5.2.2.4.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.41 *Inter-segment analysis of variance for PM_1 (logged value)*

Source	**SS**	**Df**	**MS**	**F**	**Prob >F**
Between Groups	164.013425	6	27.3355708	79.61	**<0.05**
Within groups	1904.26299	5546	0.343357914		
Total	2068.27641	5552	0.372528173		

Table 5.41 shows that the overall model is statistically significant at p level <0.05. This means that the level of PM_1 for at least one of segments of the car journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.42).

Table 5.42 *Bonferroni matrix for the effect of car segments on PM_1 exposure*

Row Mean –Col Mean (log)	**C1 12.36**	**C2 12.35**	**J1 8.98**	**J2 8.72**	**W1 2.78**	**W2 9.90**
C2 12.35	-0.01 p=1					
J1 8.98	**-3.38 p<0.05**	**-3.37 p<0.05**				
J2 8.72	**-3.64 p<0.05**	**-3.63 p<0.05**	**-0.26 p<0.05**			
W1 2.78	**-9.58 p<0.05**	**-9.57 p<0.05**	**-6.2 p<0.05**	**-5.94 p<0.05**		
W2 9.90	**-2.46 p<0.05**	**-2.45 p<0.05**	0.01 p=1	**1.18 p<0.05**	**7.12 p<0.05**	
W3 2.97	**-9.39 p<0.05**	**-9.38 p<0.05**	**6.01 p<0.05**	**-5.75 p<0.05**	**0.19 p<0.05**	**-6.93 p<0.05**

Table 5.42 indicates that the $PM_{2.5}$ levels had significant differences between all group means at p<0.05 except between journey one and the second waiting period at the centre of town.

5.2.2.5 UFP

5.2.2.5.1 Descriptive Statistics

Table 5.43 *Descriptive statistics for UFPs for car segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	17106	10319	23893	5499	2989	340523	41056	1.89
J1	83479	80692	86266	50508	4981	970369	89133	19.03
C1	78733	72287	85179	29672	4567	1060014	90161	3.54
W2	22851	22333	23368	16522	906	221331	18685	22.42
C2	41895	39225	44565	18403.0	251	226429	35410	3.47
J2	75348	72227	78470	38906	3203	830152	88668	16.02
W3	27563	23970	31156	32880	1968	71683	0.67	15290

The exposure during the first journey had the highest UFP exposure compared to all the other segments in the car journey. This was followed by car park one and journey two respectively. The UFP level during the final waiting period exceeded the exposure levels of UFP in the other two waiting periods (Table 5.43). The box and whisker plot below (Figure 5.20) displays the UFP levels for each of the segment in sequential order.

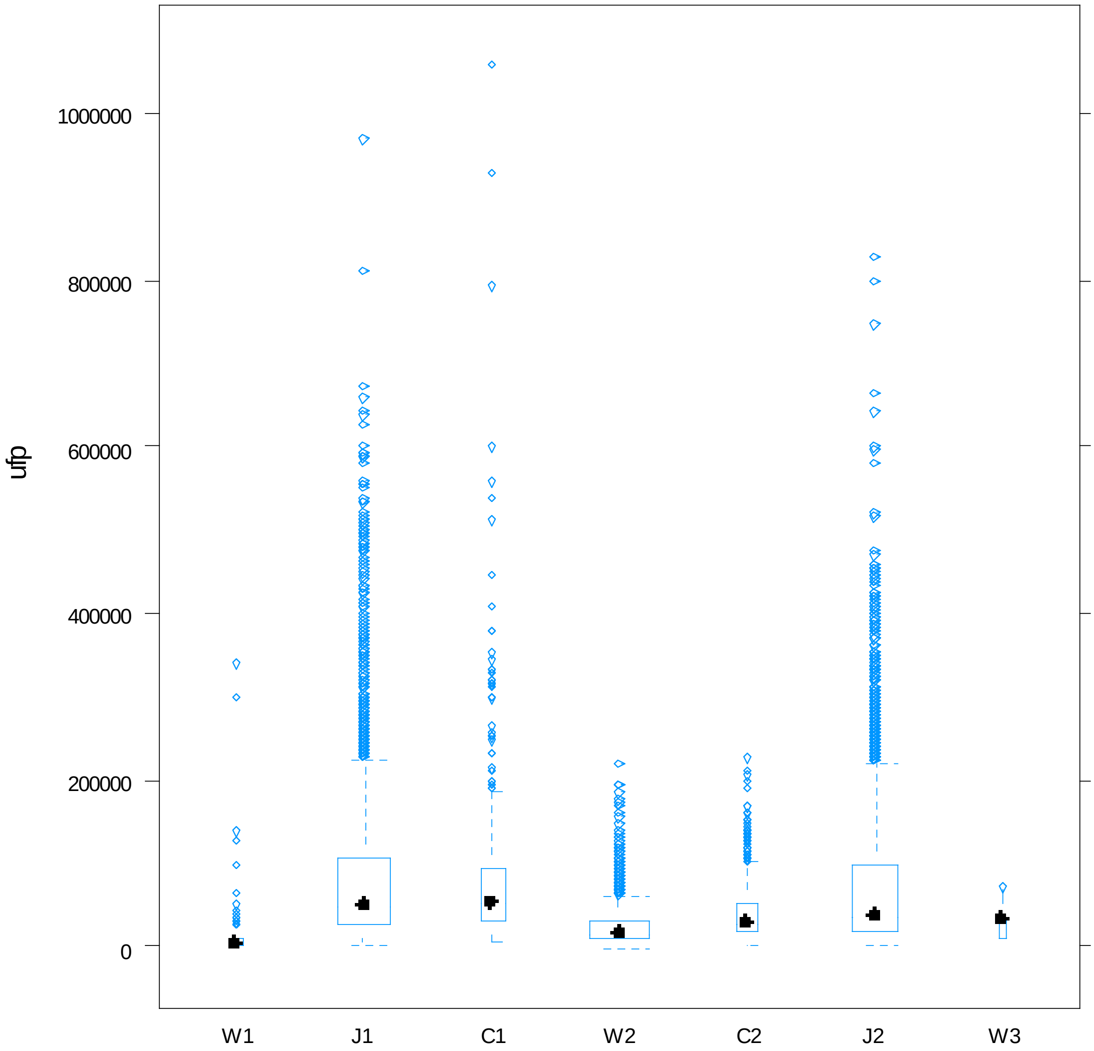


Figure 5.20 *Box and whisker plot showing the UFP exposure for car segments*

5.2.2.5.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 5.44 *Inter-segment analysis of variance for UFPs (logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	3734.99314	6	622.498856	812.26	**<0.05**
Within groups	10493.3011	13692	0.766381908		
Total	14228.2942	13698	1.03871326		

Table 5.44 shows that the overall model is statistically significant at p level <0.05. This means that the UFP level for at least one of segments of the car journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 5.45).

Table 5.45 *Bonferroni matrix for the effect of car segments on UFP exposure*

Row Mean –Col Mean (log)	**C1 78733**	**C2 41895**	**J1 83479**	**J2 75348**	**W1 17106**	**W2 22851**
C2 41895	**-36838 p<0.05**					
J1 83479	4746 p=1	**41584 p<0.05**				
J2 75348	**-3385 p<0.05**	**-34547 p<0.05**	**-8131 p<0.05**			
W1 17106	**-61627 p<0.05**	**-24789 p<0.05**	**-66373 p<0.05**	**-58242 p<0.05**		
W2 22851	**-55882 p<0.05**	**-19044 p<0.05**	**-60628 p<0.05**	**-52497 p<0.05**	**5745 p<0.05**	
W3 27563	**-51170 p<0.05**	-14322 p=0.088	**-55916 p<0.05**	**-47785 p<0.05**	**10457 p<0.05**	4712 p=0.207

Table 5.45 indicates that the UFP levels had significant differences between all group means at p<0.05 except between journey one and car park one. The final waiting period was also not seen to be significantly related to car park two and the second waiting period at the centre of town.

5.2.2.6 Summary

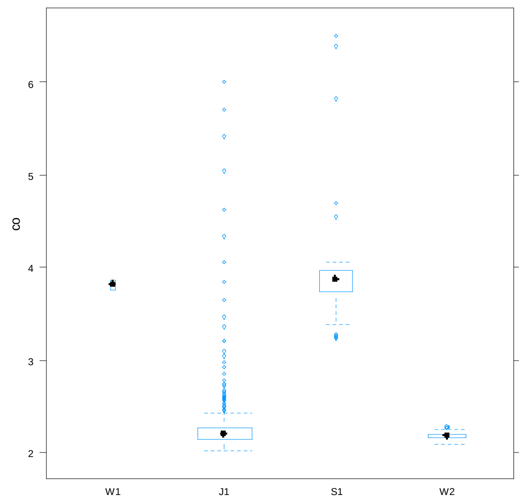
Although the time spent in the sheltered car park lasted less than four minutes, the CO exposure was higher in the aforementioned micro-environment than any of the other segments, including the actual car journeys. In terms of particulate pollution, the centre of town proved to be the most polluting for PM_{10} and $PM_{2.5}$. However, the PM_{10} and $PM_{2.5}$ levels in the car park were significantly higher compared to the journeys and the remaining waiting periods. For PM_1 exposure, the car park was seen to be the most polluting micro-environment. While examining UFP exposures across the segments, journey one along Main North Road had the highest UFP count.

5.3 Evidence of Elevated Exposures on Individual Journeys in Micro-Environments

This section includes examples of peak exposures in transport micro-environments on individual journeys. As is evidenced by the figures below, pollutant exposures reach peak levels in micro-environments such as sheltered car parks and indoor and outdoor bus stops. The peak values represented in the figures below significantly exceed the mean exposure for the entire journey.

5.3.1 Peak Exposure in Bus Stop

5.3.1.1 Outdoor Bus Stop



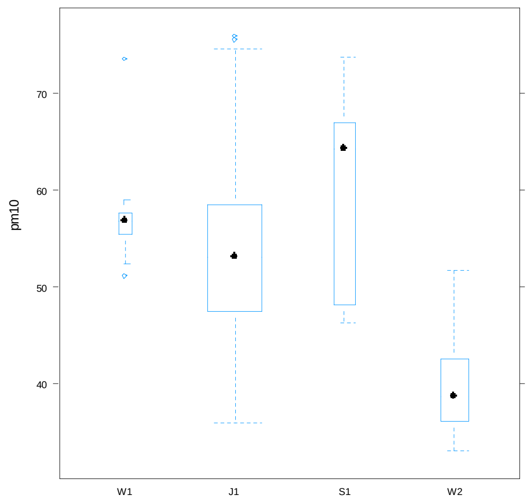
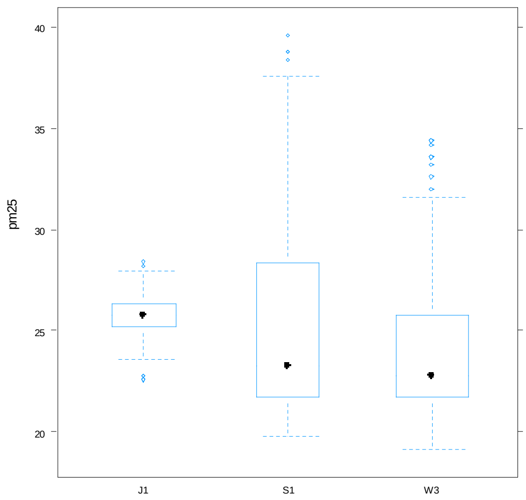


Figure 5.21
Elevated CO exposure in the outdoor bus stop. The elevated CO exposure at the bus stop exceeds the mean exposure during the overall journey

Date: 17.03.2009
Time of day: AM
Mean CO exposure: 3.07 ppm

Figure 5.22
Elevated PM_{10} exposure in the outdoor bus stop. The elevated PM_{10} exposure at the bus stop exceeds the mean exposure during the overall journey

Date: 10.03.2009
Time of day: AM
Mean CO exposure: 43.26 µg^3



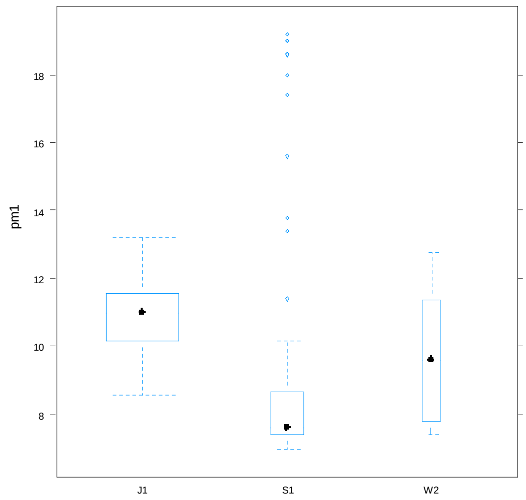


Figure 5.23
Elevated $PM_{2.5}$ exposure in the outdoor bus stop. The elevated $PM_{2.5}$ exposure at the bus stop exceeds the mean exposure during the overall journey

Date: 13.03.2009
Time of day: PM
Mean CO exposure: 22.88 μg^3

Figure 5.24
Elevated PM_1 exposure in the outdoor bus stop. The elevated PM_1 exposure at the bus stop exceeds the mean exposure during the overall journey

Date: 20.03.2009
Time of day: AM
Mean CO exposure: 12.98 μg^3

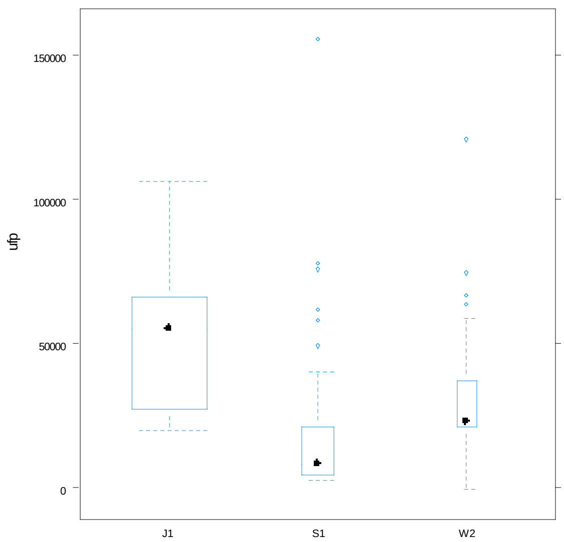
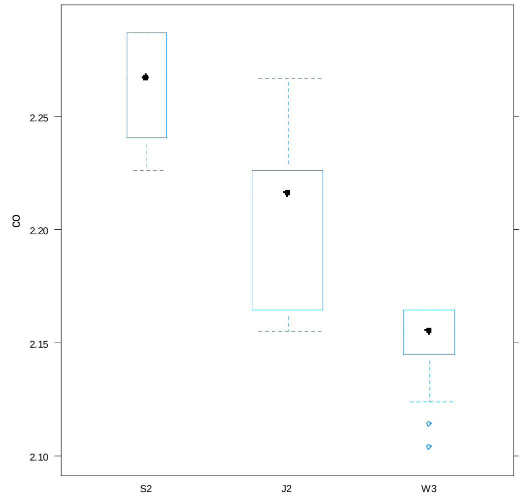


Figure 5.25
Elevated UFP exposure in the outdoor bus stop. The elevated UFP exposure at the bus stop exceeds the mean exposure during the overall journey

Date: 20.03.2009
Time of day: PM
Mean CO exposure: 74332

5.3.1.2 Indoor Bus Stop



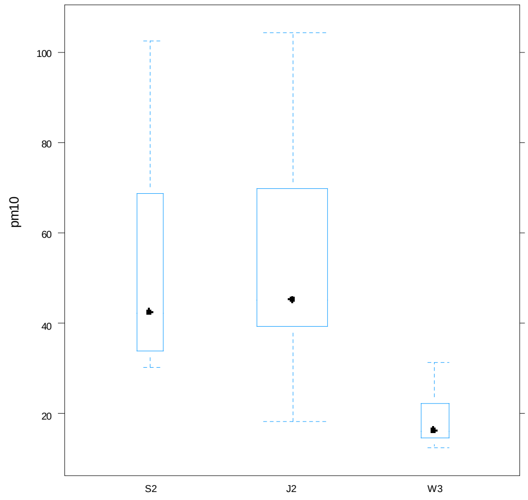
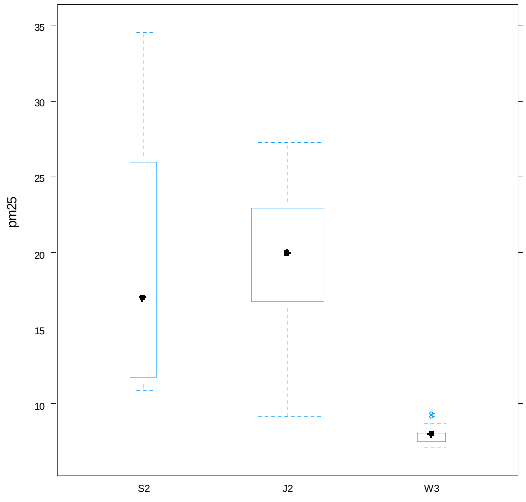


Figure 5.26 Elevated CO exposure in the indoor bus stop. The elevated CO exposure at the bus stop exceeds the mean exposure during the overall journey Date: 20.03.2009 Time of day: AM Mean CO exposure: 3.07 ppm	**Figure 5.27** Elevated PM_{10} exposure in the indoor bus stop. The elevated PM_{10} exposure at the bus stop exceeds the mean exposure during the overall journey Date: 24.03.2009 Time of day: AM Mean CO exposure: 43.26 μg^3



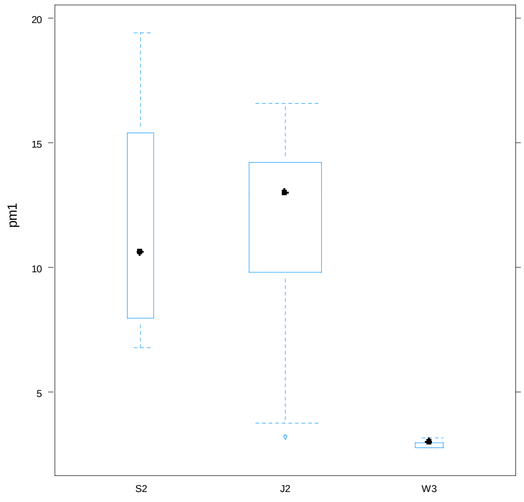
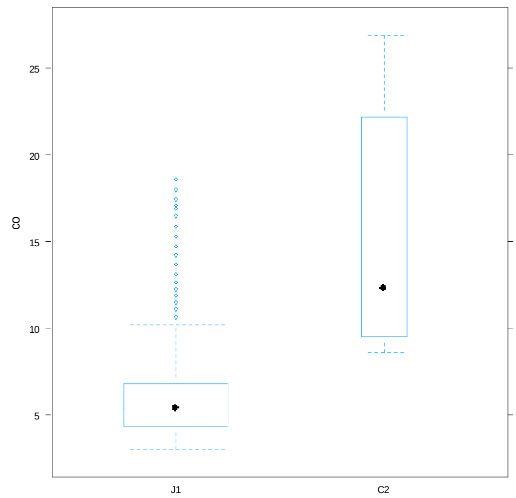


Figure 5.28 Elevated $PM_{2.5}$ exposure in the indoor bus stop. The elevated $PM_{2.5}$ exposure at the bus stop exceeds the mean exposure during the overall journey Date: 04.03.2009 Time of day: AM Mean CO exposure: 22.88 μg^3	**Figure 5.29** Elevated PM_1 exposure in the indoor bus stop. The elevated PM_1 exposure at the bus stop exceeds the mean exposure during the overall journey Date: 04.03.2009 Time of day: AM Mean CO exposure: 43.26 μg^3

5.3.2 Elevated Exposure in Sheltered Car Park



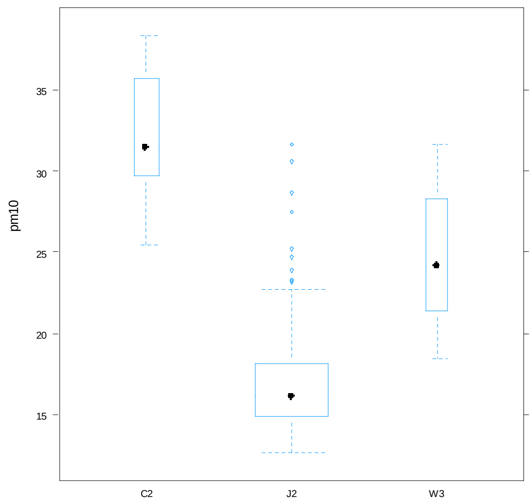
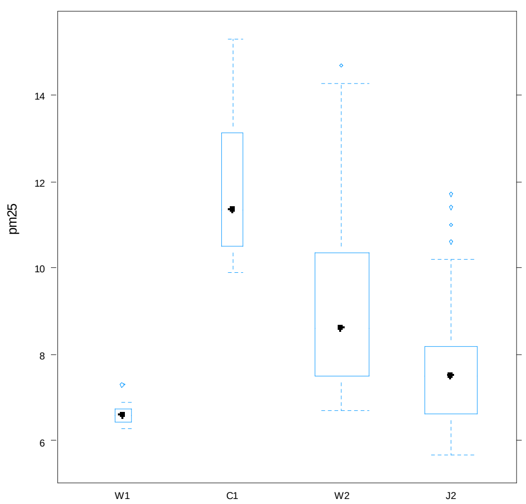


Figure 5.30
Elevated CO exposure in the sheltered car park. The elevated CO exposure at the car park exceeds the mean exposure during the overall journey

Date: 10.03.2009
Time of day: PM
Mean CO exposure: 4.15 ppm

Figure 5.31
Elevated PM_{10} exposure in the sheltered car park. The elevated PM_{10} exposure at the car park exceeds the mean exposure during the overall journey

Date: 10.03.2009
Time of day: AM
Mean CO exposure: 36.74 μg^3



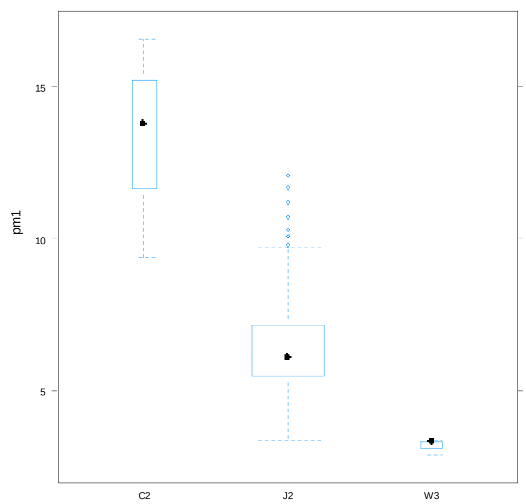


Figure 5.32
Elevated $PM_{2.5}$ exposure in the sheltered car park. The elevated $PM_{2.5}$ exposure at the car park exceeds the mean exposure during the overall journey

Date: 04.03.2009
Time of day: AM
Mean CO exposure: 22.88 μg^3

Figure 5.33
Elevated PM_1 exposure in the sheltered car park. The elevated PM_1 exposure at the car park exceeds the mean exposure during the overall journey

Date: 04.03.2009
Time of day: AM
Mean CO exposure: 43.26 μg^3

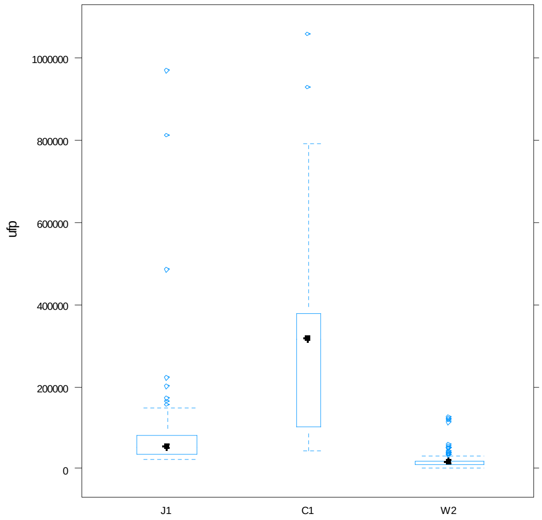


Figure 5.34
Elevated UFP exposure in the sheltered car park. The elevated UFP exposure at the car park exceeds the mean exposure during the overall journey

Date: 05.03.2009
Time of day: PM
Mean CO exposure: 56123

5.3.3 Summary

Exposures in certain micro-environments, namely the sheltered car park, and the indoor and outdoor bus stops greatly exceeded the mean exposures for the entire journey. This was true for all five monitored pollutants except in the case of UFPs in the indoor car park.

5.4 Other factors

This section will present the results for the effects of wind speed and time of day on pollution exposure.

5.4.1.1 Wind Speed

5.4.1.2 Descriptive Statistics

Table 5.46 *Descriptive statistics for high and low wind speed on overall pollution level*

Speed	CO Mean	CO SD	PM_{10} Mean	PM_{10} SD	$PM_{2.5}$ Mean	$PM_{2.5}$ SD	PM_1 Mean	PM_1 SD	UFP Mean	UFP SD
High	2.98	1.90	36.91	30.59	18.00	11.53	8.15	4.91	31732	53225
Low	3.45	1.80	41.18	40.45	22.24	19.36	12.95	12.98	56638	71134
All Groups	3.21	1.87	38.86	35.49	19.93	15.74	10.34	9.78	43228	63363

Low wind speed was a precursor for higher levels of pollution across all five pollutants (Table 5.46). Table 5.47, which presents the t-test results for the low and high wind comparison, shows that the difference in pollutant levels resulting from different wind speeds is significant at the level $p<0.05$.

5.4.1.3 T-test Comparison

Table 5.47 *T-test results for effect of high and low wind speed on overall pollution level*

Pollutant	Mean High	Mean Low	df	p
CO	2.98	3.45	67953	**$p<0.05$**
PM_{10}	36.91	41.18	46217	**$p<0.05$**
$PM_{2.5}$	18.00	22.24	46217	**$p<0.05$**
PM_1	8.15	12.95	46217	**$p<0.05$**
UFP	31732	56638	43995	**$p<0.05$**

5.4.1.4 Time of Day

5.4.1.5 Descriptive Statistics

Table 5.48 *Descriptive statistics for effect of time of day on overall pollution level*

Time of Day	CO Mean	CO SD	PM_{10} Mean	PM_{10} SD	$PM_{2.5}$ Mean	$PM_{2.5}$ SD	PM_1 Mean	PM_1 SD	UFP Mean	UFP SD
AM	3.34	1.73	39.48	29.27	21.09	17.65	12.21	12.19	59808	78118
PM	3.03	2.02	38.15	41.43	18.61	13.10	8.21	5	23586	28822
All Groups	3.21	1.87	38.86	35.49	19.93	15.74	10.34	9.78	43228	63364

Table 5.48 shows that higher levels of pollution across all five pollutants were experienced in the morning journeys when compared to afternoon trips.

5.4.1.6 T-Test Comparison

Table 5.49 *T-test results for effect of time of day on overall pollution level*

Pollutant	Mean AM	Mean PM	df	P
CO	3.34	3.03	67953	**$p<0.05$**
PM_{10}	39.48	38.15	46217	**$p<0.05$**
$PM_{2.5}$	18.61	18.61	46217	**$p<0.05$**
PM_1	8.21	8.21	46217	**$p<0.05$**
UFP	23586	23586.30	43995	**$p<0.05$**

Table 5.49, which presents the t-test results for the comparison between pollutant levels on morning and afternoon journeys, shows that the difference in pollutant levels resulting from different wind speeds is significant at the level $p<0.05$.

5.4.2 Summary

Both wind speed and time of day were significant factors that influenced pollution levels. Low wind speed resulted in higher pollution levels across all the monitored pollutants. Similarly, the pollution levels were higher for all five pollutants during the morning journeys compared to the afternoon ones.

CHAPTER SIX

Results: Auckland

6.0 Introduction

The objective of this chapter is to present the results of the fieldwork carried out in Auckland. While Section 6.1 will include results for the inter-modal comparison for the four modes- bus, car, bike and train, Section 6.2 will demonstrate the results for the different segments of the car, bus and train journeys. Section 6.3 will include evidence of elevated exposures in individual journeys at the underground car park and the outdoor bus stop and train station. Finally, Section 6.4 will contain the results for other factors, which influence pollution exposure levels on commuter journeys. These include wind speed and the time of day. Sections 6.1 and 6.2 will include descriptive statistics and the results produced from ANOVA and the post-hoc Bonferroni test to determine the statistically significant difference between the different groups and box and whisker plots showing the exposures for the different modes. Section 6.3 will include box and whisker plots showing elevated exposures in certain micro-environments on individual journeys. Section 6.4 will present descriptive statistics and results from the independent t-tests that were carried out to ascertain the effect wind speed and the time of day had on exposure levels.

As with the data collected in Christchurch, the pollution exposure concentrations distributions for Auckland were highly skewed so the commuter exposure data was log transformed. Logarithmic transformation of the raw data produced more normally distributed data, so subsequent analyses were done using the log- transformed data. Due to equipment failure, exposure for UFPs for all modes and particulate exposure (PM_{10}, $PM_{2.5}$ and PM_1) for train will not be included in the analysis.

6.1 Intermodal Comparisons

6.1.1 Carbon Monoxide

6.1.1.1 Descriptive Statistics

Table 6.1 *Inter- modal descriptive statistics for CO*

Mode	N	Mean	CI - 95%	CI 95%	Median	Min	Max	SD
Car	25	7.11	7.06	7.16	6.78	1.00	29.35	3.06
Bike	24	4.58	4.53	4.63	4.02	1.63	115.15	2.90
Train	25	3.29	3.28	3.31	3.04	1.00	10.64	0.89
Bus	24	3.50	3.47	3.52	3.30	1.00	16.55	1.44

Table 6.1 summarises the statistical results of CO levels in different transport modes. The CO level in a car was significantly higher compared to the other modes. It was 1.6 times higher than the CO level experienced by the cyclist, 2.16 times higher than the CO level on the train, and finally, 2.03 times higher than the CO level on the bus. The inter-modal mean comparison for CO is presented in a box and whisker plot below (Figures 6.1 and 6.2). While Figure 6.1 shows the average concentration per trip, Figure 6.2 shows the average concentration for the total number of trips for each of the four modes. The width of the boxes is proportional to the time spent in each segment. The vertical extent of the boxes, which include the whiskers and the outliers, shows the overall distribution of the exposure data. The point in the middle represents the median. While Figure 6.1 shows the average concentration per trip, Figure 6.2 shows the average concentration for the total number of trips.

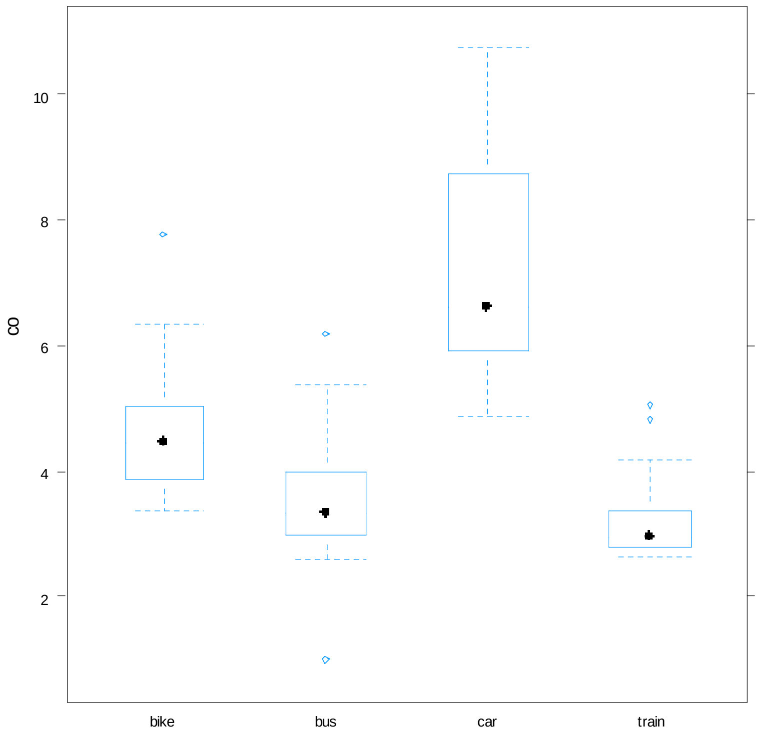


Figure 6.1 *Box and Whisker Plot showing the mean inter- modal CO exposures per trip*

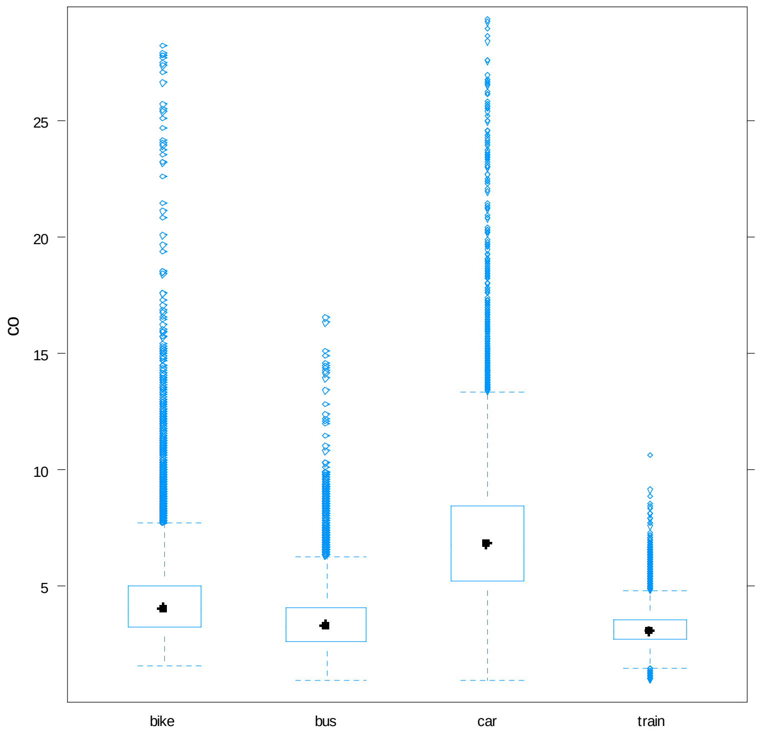


Figure 6.2 *Box and whisker plot showing the mean inter-modal CO exposures for total number of trips*

6.1.1.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.2 *Inter-modal analysis of variance for CO (logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	787.752614	3	262.584205	10141.66	**<0.05**
Within groups	1441.28387	55666	.025891637		
Total	2229.03649	55669	.040040893		

Table 6.2 shows that the overall model is statistically significant at p value <0.05. This means that the CO level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is computed in the table below (Table 6.3).

Table 6.3 *Bonferroni matrix for the effect of modal choice on CO exposure*

Row Mean –Col Mean	**Bike 4.58**	**Bus 3.50**	**Car 7.11**
Bus 3.50	**-1.08 p<0.05**		
Car 7.11	**2.53 p<0.05**	**3.61 p<0.05**	
Train 3.29	**-1.29 p<0.05**	**-0.21 p<0.05**	**-3.82 p<0.05**

The Bonferroni test (Table 6.3) shows that the all group means are statistically significantly different from each other. The car driver was exposed to the highest level of CO, and this was followed by the exposure for the cyclist. The train commuter experienced the lowest CO level exposure.

6.1.2 PM_{10}

6.1.2.1 Descriptive Statistics

Table 6.4 *Inter- modal descriptive statistics for PM_{10}*

Mode	N	Mean	CI - 95%	CI 95%	Median	Min	Max	SD
Car	25	23.80	23.48	24.13	19.40	5.40	229.70	15.79
Bike	24	25.94	25.30	26.59	21.26	5.46	1098.83	35.81
Bus	24	23.50	23.33	23.67	22.14	2.30	96.62	9.82

Concerning PM_{10} exposure, the cyclist was exposed to the highest level of PM_{10} with a mean exposure level of 25.94 μg^3 and the bus commuter had the lowest mean exposure of 23.50 μg^3. Although the variation across the mode was not particularly high, the maximum exposure for the cyclist was very high at over 1000 μg^3. While Figure 6.3 shows the average per trip concentration for each mode, Figure 6.4 illustrates the overall average concentration for the different modes.

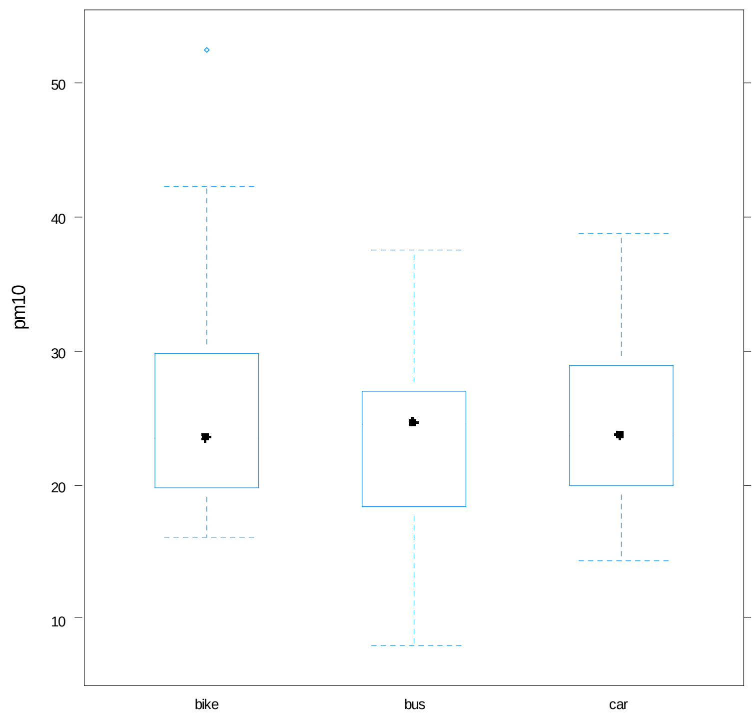


Figure 6.3 *Box and whisker plot showing the mean inter- modal PM_{10} exposures per trip*

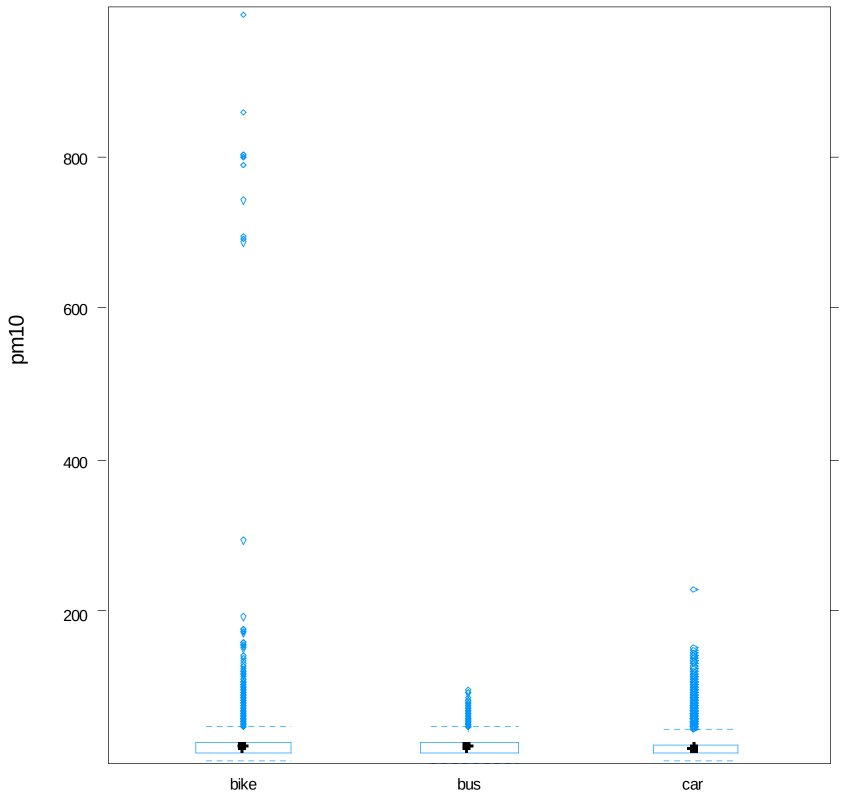


Figure 6.4 *Box and Whisker Plot showing the mean inter- modal PM_{10} exposures for total number of trips*

6.1.2.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.5 *Inter-modal analysis of variance for PM_{10} (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	6.27758164	2	3.13879082	81.52	**<0.05**
Within groups	1276.31809	33147	.038504785		
Total	1282.59568	33149	.038691836		

These results show that the overall model is statistically significant at p value <0.05. This means that PM_{10} level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is computed in the table below (Table 6.6).

Table 6.6 *Bonferroni matrix for the effect of modal choice on PM_{10} exposure*

Row Mean – Col Mean (log)	Bike 25.94	Bus 23.50
Bus 23.50	**-2.44 p<0.05**	
Car 23.80	**-2.14 p<0.05**	**-.03 p<0.05**

The Bonferroni test (Table 6.6) shows that the all group means are statistically significantly different from each other. The cyclist was exposed to the highest level of PM_{10}. The pollutant exposure was higher for the car driver than it was for the bus commuter.

6.1.3 $PM_{2.5}$

6.1.3.1 Descriptive Statistics

Table 6.7 *Inter- modal descriptive statistics for $PM_{2.5}$*

Mode	N	Mean	CI - 95%	CI 95%	Median	Min	Max	SD
Car	25	17.85	17.56	18.15	13.60	4.00	144.40	14.50
Bike	24	15.87	15.48	16.27	12.82	3.13	696.65	21.91
Bus	24	22.77	22.53	23.00	20.15	2.30	131.09	13.38

The exposure for $PM_{2.5}$ for the bus users was 22.77 μg^3, which was significantly higher compared to other commuters. The commuter who travelled by car had a lower exposure at 17.85 μg^3. The lowest $PM_{2.5}$ exposure was experienced by the cyclist (15.87 μg^3). Figures 6.5 and 6.6 show box and whisker plots of average concentration per trip and total average concentration across modes respectively.

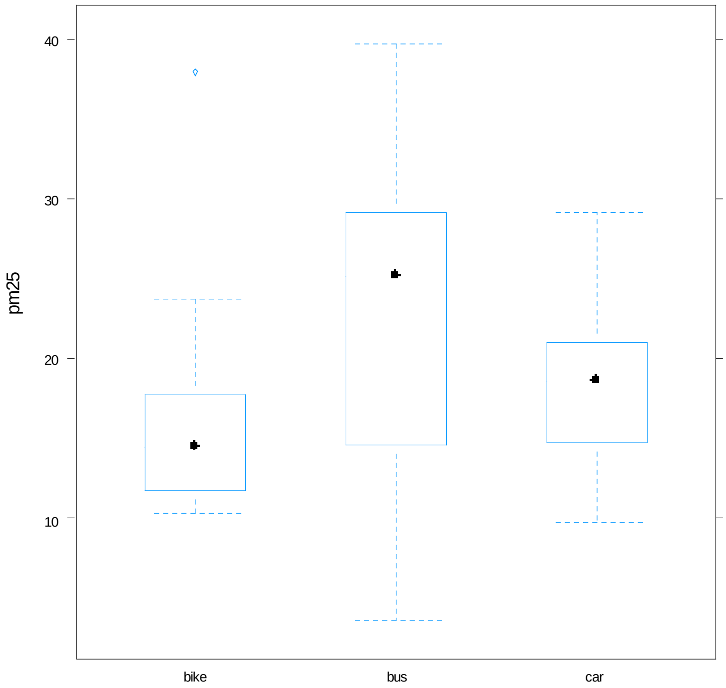


Figure 6.5 *Box and Whisker Plot showing the mean inter- modal $PM_{2.5}$ exposures per trip*

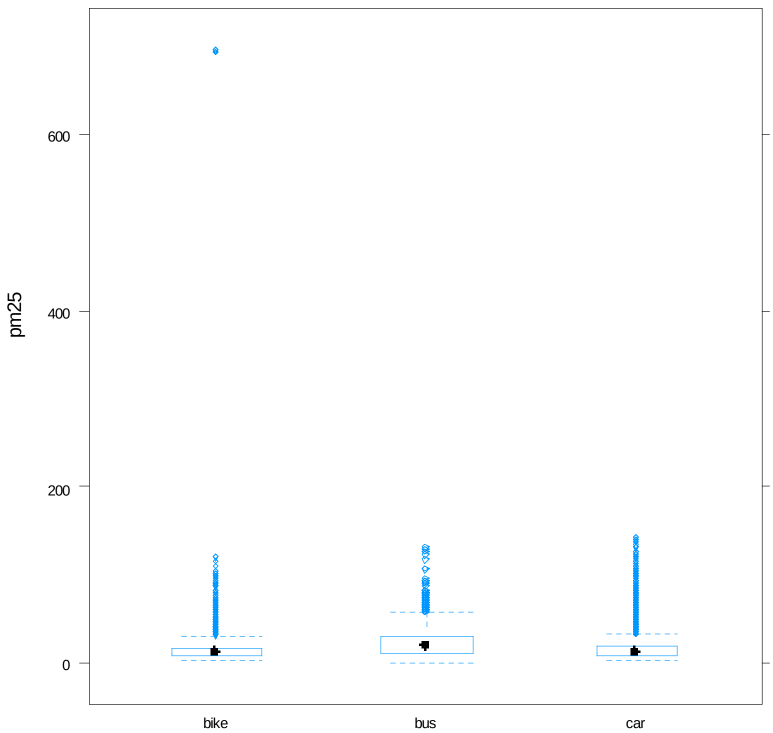


Figure 6.6 *Box and whisker plot showing the mean inter- modal $PM_{2.5}$ exposures for total number of trips*

6.1.3.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.8 *Inter-modal analysis of variance for $PM_{2.5}$ (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	140.394062	2	70.1970309	1201.50	**<0.05**
Within groups	1936.5981	33147	. .058424536		
Total	2076.99216	33149	.062656254		

These results show that the overall model is statistically significant at p level <0.05. This means that the $PM_{2.5}$ level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of 0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 6.9).

Table 6.9 *Bonferroni matrix for the effect of modal choice on $PM_{2.5}$ exposure*

Row Mean – Col Mean (log)	**Bike 15.87**	**Bus 22.77**
Bus 22.77	**6.83 p<0.05**	
Car 17.85	**1.98 p<0.05**	**-4.92 p<0.05**

As displayed by Table 6.9, the Bonferroni test yields significant differences between all group means at $p<0.05$. The pollutant exposure for the bus user was higher than the level experienced by the car driver or the cyclists. The cyclist was exposed to the lowest $PM_{2.5}$ levels.

6.1.4 PM_1

6.1.4.1 Descriptive Statistics

Table 6.10 *Inter- modal descriptive statistics for PM_1*

Mode	N	Mean	CI - 95%	CI 95%	Median	Min	Max	SD
Car	25	13.29	13.88	13.88	8.90	1.70	141.80	14.49
Bike	24	10.10	9.95	10.26	7.82	1.55	119.83	8.69
Bus	24	16.62	16.42	16.81	13.55	1.80	102.14	11.05

Table 6.10 shows that the personal exposure for $PM_1$was significantly higher for the bus commuter compared to the car user and the cyclist. The bus commuter was exposed to rates of PM_1 1.25 times higher than the car driver was, and 1.65 times higher than the cyclist was (Figures 6.7 and 6.8).

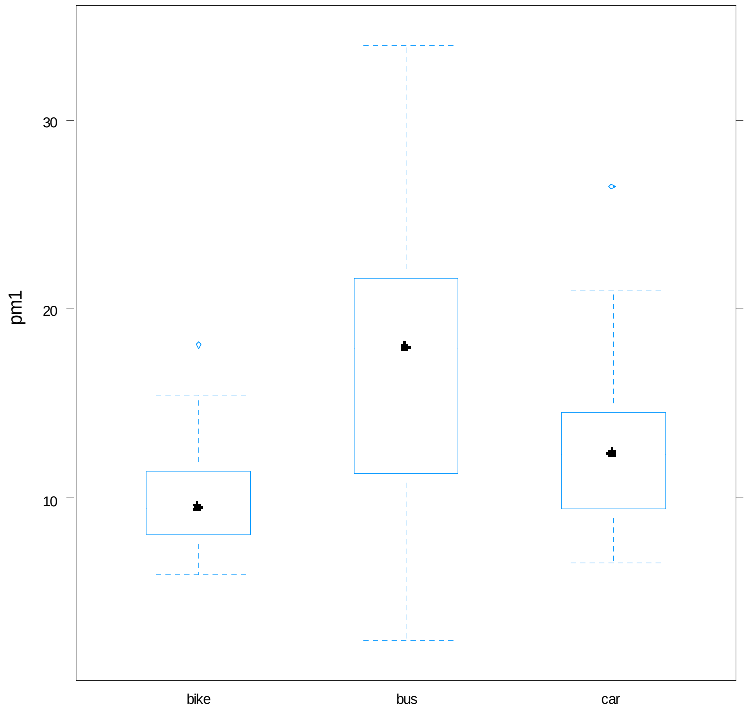


Figure 6.7 *Box and Whisker Plot showing the mean inter- modal PM_1 exposures per trip*

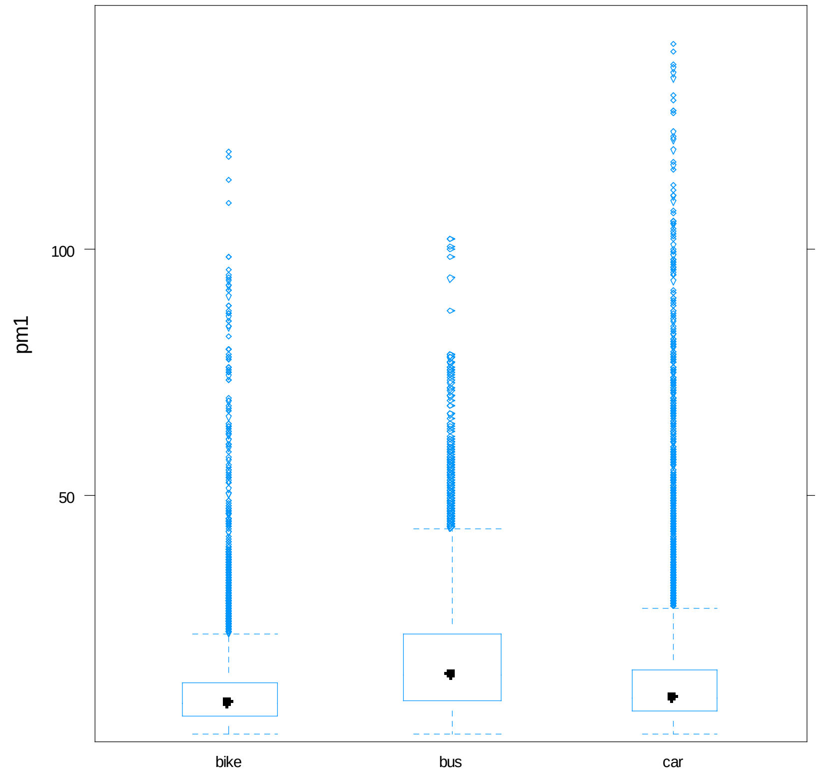


Figure 6.8 *Box and whisker plot showing the mean inter- modal PM_1 exposures*

6.1.4.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.11 *Inter-modal analysis of variance for PM_1 (logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	305.462965	2	152.731483	152.731483	**<0.05**
Within groups	2766.28316	33147	.083455008		
Total	3071.74612	33149	.09266482		

These results show that the overall model is statistically significant at p level <0.05. The PM_1 level for at least one of the modes of transportation differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means is displayed in the Bonferroni table below (Table 6.12).

Table 6.12 *Bonferroni matrix for the effect of modal choice on PM_1 exposure*

Row Mean – Col Mean (log)	Bike 10.10	Bus 16.62
Bus 16.62	6.52 $p<0.05$	
Car 13.58	3.48 $p<0.05$	-3.04 $p<0.05$

The post- hoc test reveals that the Bonferroni test yields significant differences between all group means at $p<0.05$. The pollutant exposure for the bus user was higher compared to the car driver and the cyclist. Similarly, the car commuter had higher a $PM_{2.5}$ level than the cyclist.

6.1.4 Summary: Inter-Modal Comparison

In terms of inter-modal comparison for pollutants, the type of mode was a significant factor in influencing personal exposure while traveling. For CO exposure, the car was the most polluting mode, while the train was the least polluting. Although the train commuter was exposed to a lower level of CO than the bus and car commuter was, they were exposed to a higher level of CO than the cyclist was. However, while examining PM_{10} exposure, the cycling was seen to be mode most affected by the pollutant and the bus commuting, the least. Although the exposure levels were not highly variant across the modes, the cyclist was exposed to very elevated levels during the journey; the maximum level of PM_{10} for the cyclist being 1098.83 μg^3. The bus commuter was exposed to the highest levels of $PM_{2.5}$ and PM_1. The cyclist, on the other hand, had the lowest $PM_{2.5}$ and PM_1 exposures.

6.2 Segment Comparison for Bus and Car Journeys

This section will be divided into three sub-sections containing results for the segment comparisons for the bus (Section 6.2.1), car (Section 6.2.2) and train (6.2.3) journeys. The bus journey was divided four different segments[1]. They are as follows:

- W1: Waiting period before the start of the journey
- J: Journey between the Auckland Central Business District (ACBD) and Mt. Mt. Albert Road
- S: Waiting period at the bus stop
- W2: Waiting period at the end of the journey

Similarly, the car journey was also divided into four segments. They were:

- W1: Waiting period before the start of the journey
- J: Journey between the Auckland Business District (ACBD) and Mt. Albert Road
- CP: Time spent in the underground car park
- W2: Waiting period after the end of the journey

Finally, the train journey was divided into five segments. They were:

- W1: Waiting period before the start of the journey
- J: Journey between the Auckland Business District (ACBD) and Mt. Albert Road
- TS: Time spent at the outdoor train station
- BS: Time spent at Britomart, the indoor metro station
- W2: Waiting period after the end of the journey

Each sub-section will consist of the descriptive statistics for every segment. The averages will also be displayed graphically in a box and whisker plot. ANOVA results

[1] Since all journeys across the modes had the same starting, mid- and end, W1, and W2 are common to all bus, car and train journeys.

and the post- hoc Bonferroni test to determine the statistically significant difference between the different segments will also be included.

6.2.1 Bus Journey

6.2.1.1 CO

6.2.1.1.1 Descriptive Statistics

Table 6.13 *Descriptive statistics for carbon monoxide for bus segments*

Mode	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	2.46	2.41	2.51	2.41	1.00	7.89	1.03	6.40
J	3.84	3.81	3.87	3.60	1.00	15.11	1.45	41.43
S	3.15	3.10	3.20	2.81	1.00	14.39	1.29	9.83
W2	3.07	3.02	3.12	2.75	1.00	16.55	1.22	9.63

Table 6.13 shows that the CO exposure was highest during the journey. This was followed by the exposure at the bus stop. The two waiting periods had the lowest CO levels. The box and whisker plot below (Figure 6.9) represents the exposure for CO for each of the segments in the bus journey. The width of the boxes is proportional to the time spent in each segment. The vertical extent of the boxes, which include the whiskers and the outliers, shows the overall distribution of the exposure data. The point in the middle represents the median.

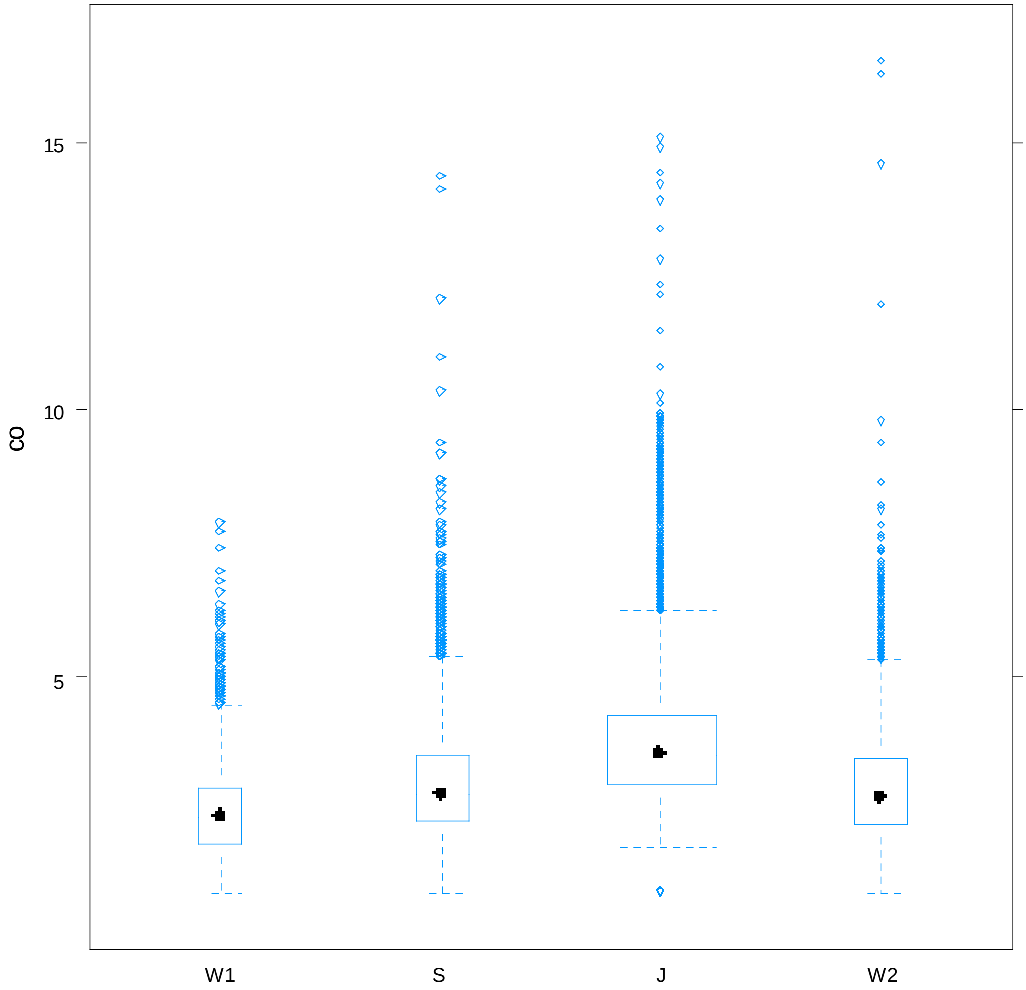


Figure 6.9 *Box and whisker plot showing the mean CO exposure for bus segments*

6.2.1.1.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.14 *Inter-segment analysis of variance for CO (logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	66.6871074	3	22.2290358	755.16	**<0.05**
Within groups	475.128566	16141	.02943613		
Total	475.128566	16141	.033561427		

These results (Table 6.14) show that the overall model is statistically significant at p level <0.05. This means that the CO level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.15).

Table 6.15 *Bonferroni matrix for the effect of bus segments on CO exposure*

Row Mean –Col Mean (log)	**J 3.84**	**S 3.15**	**W1 2.46**
S 3.15	**-0.69 p<0.05**		
W1 2.46	**-1.38 p<0.05**	**-0.69 p<0.05**	
W2 3.07	**-0.77 p<0.05**	-0.08 p=0.473	**0.61 p<0.05**

As is displayed by Table 6.15, the Bonferroni test yields significant differences between all group means at p<0.05 except between the waiting period and the bus stop.

6.2.1.2 PM_{10}

6.2.1.2.1 Descriptive Statistics

Table 6.16 *Descriptive statistics for PM_{10} for bus segments*

Mode	**Mean**	**CI - 95%**	**CI 95%**	**Median**	**Min**	**Max**	**SD**	**Average Time(m)**
W1	19.64	19.28	20.00	18.78	10.82	48.68	4.88	6.40
J	24.07	23.85	24.28	23.21	2.30	57.17	23.21	41.43
S	24.13	23.42	24.85	20.20	9.40	96.62	12.98	9.83
W2	22.12	21.79	22.44	21.97	6.50	61.60	7.44	9.63

Table 6.16 displays the distribution of PM_{10} exposure across the segments. Although the level of PM_{10} was highest during the time spent at the bus stop there was very little difference between the journey and the bus stop exposures. The PM_{10} levels in the waiting periods were significantly lower compared to the other two segments. Figure 6.10 displays the PM_{10} levels for each of the segment in sequential order.

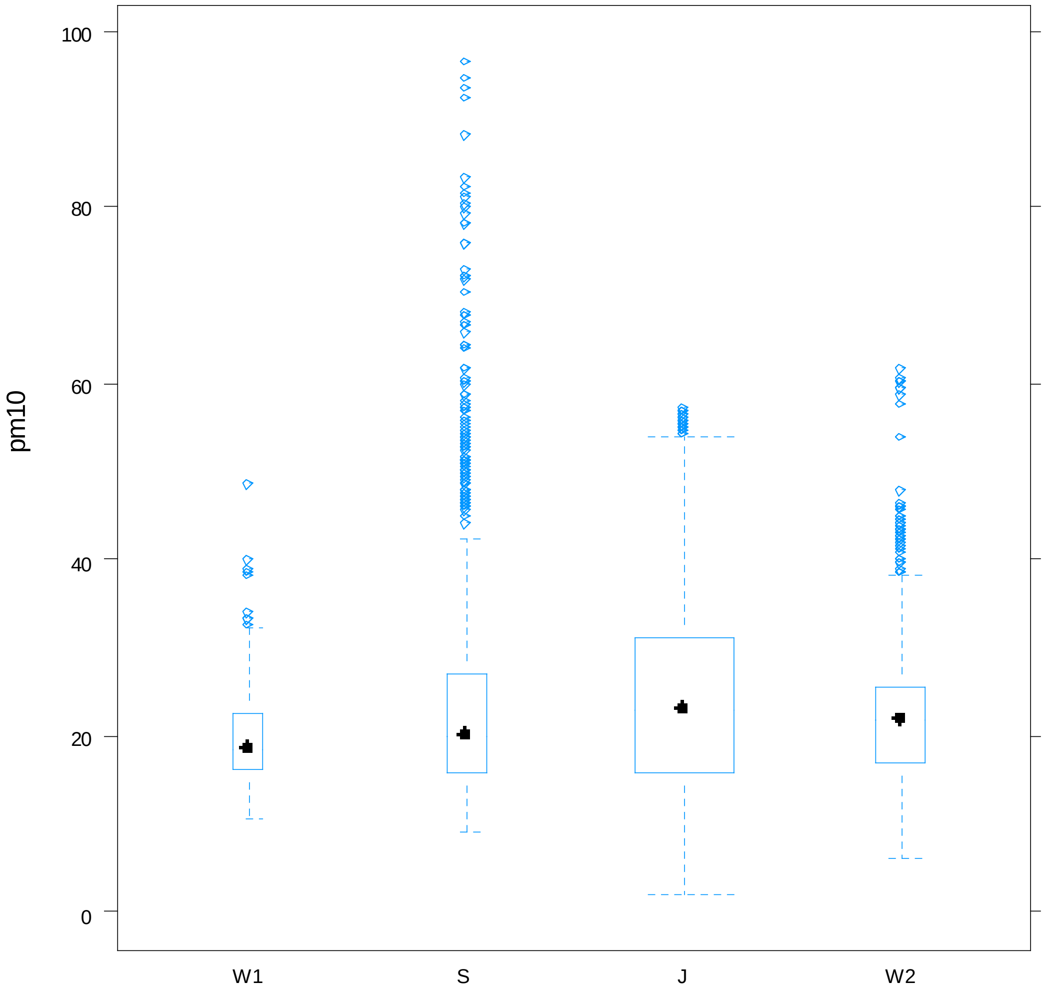


Figure 6.10 *Box and whisker plot showing the mean PM_{10} exposure for bus segments*

6.2.1.2.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.17 *Inter-segment analysis of variance for PM_{10} (logged value)*

Source	**SS**	**Df**	**MS**	**F**	**Prob >F**
Between Groups	2.83687615	3	.945625384	28.26	**<0.05**
Within groups	412.75477	12335	.033462081		
Total	415.591646	12338	. .033683875		

These results (Table 6.17) show that the overall model is statistically significant at p level <0.05. This means that the PM_{10} level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.18).

Table 6.18 *Bonferroni Matrix for the effect of bus segments on PM_{10} exposure*

Row Mean –Col Mean (log)	**J 24.07**	**S 24.13**	**W1 19.64**
S 24.13	**0.06 p<0.05**		
W1 19.64	**-4.43 p<0.05**	**-4.49 p<0.05**	
W2 22.12	**-1.95 p<0.05**	**-2.01 p<0.05**	**2.48 p<0.05**

As is displayed by Table 6.18, the Bonferroni test yields significant differences between all group means at p<0.05.

6.2.1.3 $PM_{2.5}$

6.2.1.3.1 Descriptive Statistics

Table 6.19 *Descriptive statistics for $PM_{2.5}$ for bus segments*

Mode	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	16.05	15.70	16.40	15.27	6.62	34.44	4.74	6.40
J	23.69	23.40	23.99	21.28	2.30	84.08	13.63	41.43
S	24.60	23.64	25.55	19.40	4.00	131.09	17.42	9.83
W2	20.14	19.71	20.58	19.78	2.48	81.07	9.96	9.63

As shown by Table 6.19, the bus stop was seen to be most polluting in terms of $PM_{2.5}$ exposure. The $PM_{2.5}$ level experienced during the journey was slightly lower compared to the bus stop exposure. As with both CO and PM_{10} exposure, the $PM_{2.5}$ exposures were lowest in the waiting periods. Figure 6.11 displays the $PM_{2.5}$ levels for each of the segments in sequential order.

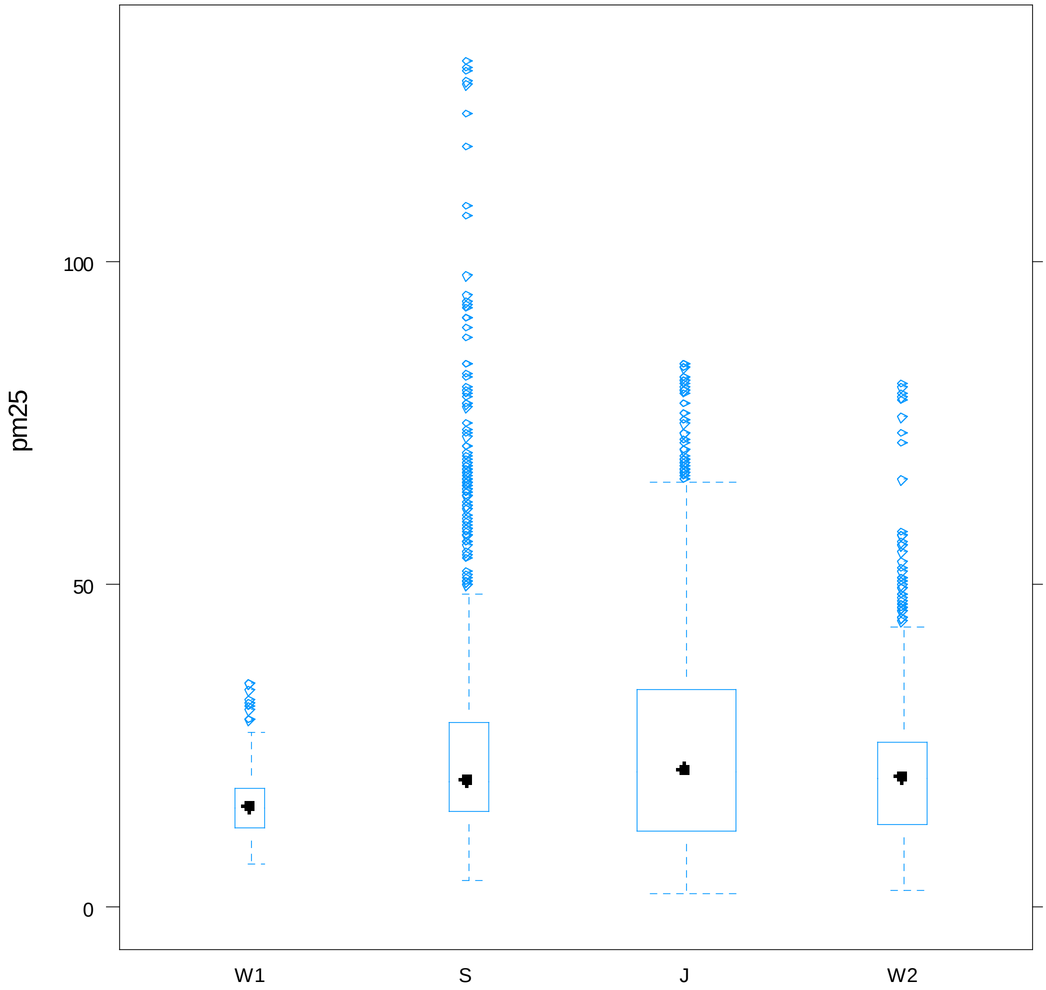


Figure 6.11 *Box and whisker plot showing the mean $PM_{2.5}$ exposure for bus segments*

6.2.1.3.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.20 *Inter-segment analysis of variance for $PM_{2.5}$ (logged value)*

Source	SS	df	MS	F	Prob >F
Between Groups	11.339555	3	3.77985165	52.75	**<0.05**
Within groups	883.949696	12335	.071661913		
Total	895.289251	12338	.072563564		

These results (Table 6.20) show that the overall model is statistically significant at p level <0.05. This means that the $PM_{2.5}$ level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.21).

Table 6.21 *Bonferroni matrix for the effect of bus segments on $PM_{2.5}$ exposure*

Row Mean – Col Mean	**J 23.69**	**S 24.60**	**W1 16.05**
S 24.60	**0.91 p<0.05**		
W1 16.05	**-7.64 p<0.05**	**-8.55 p<0.05**	
W2 20.14	**-3.55 p<0.05**	**-4.46 p<0.05**	**-4.09 p<0.05**

As is displayed by Table 6.21, the Bonferroni test yields significant differences between all group means at p<0.05.

6.2.1.4 PM_1

6.2.1.4.1 Descriptive Statistics

Table 6.22 *Descriptive statistics for PM_1 for bus segments*

Mode	**Mean**	**CI - 95%**	**CI 95%**	**Median**	**Min**	**Max**	**SD**	**Average Time(m)**
W1	8.74	8.51	8.98	8.34	3.13	26.78	3.24	6.40
J	18.17	17.92	18.42	15.15	2.00	78.49	11.60	41.43
S	16.62	15.98	17.26	13.95	1.80	102.14	11.64	9.83
W2	12.97	12.64	13.29	11.15	1.92	56.44	7.47	9.63

For PM_1, the journey was the most polluting segment ompared to all the other segments. The exposure in the bus stop was slightly lower than during the journey; however, the maximum level for the pollutant while at the bus stop was significantly higher than the maximum levels for all other segments. Both waiting periods had significantly lower pollutant levels. Figure 6.12 displays the PM_1 levels for each of the segment in sequential order.

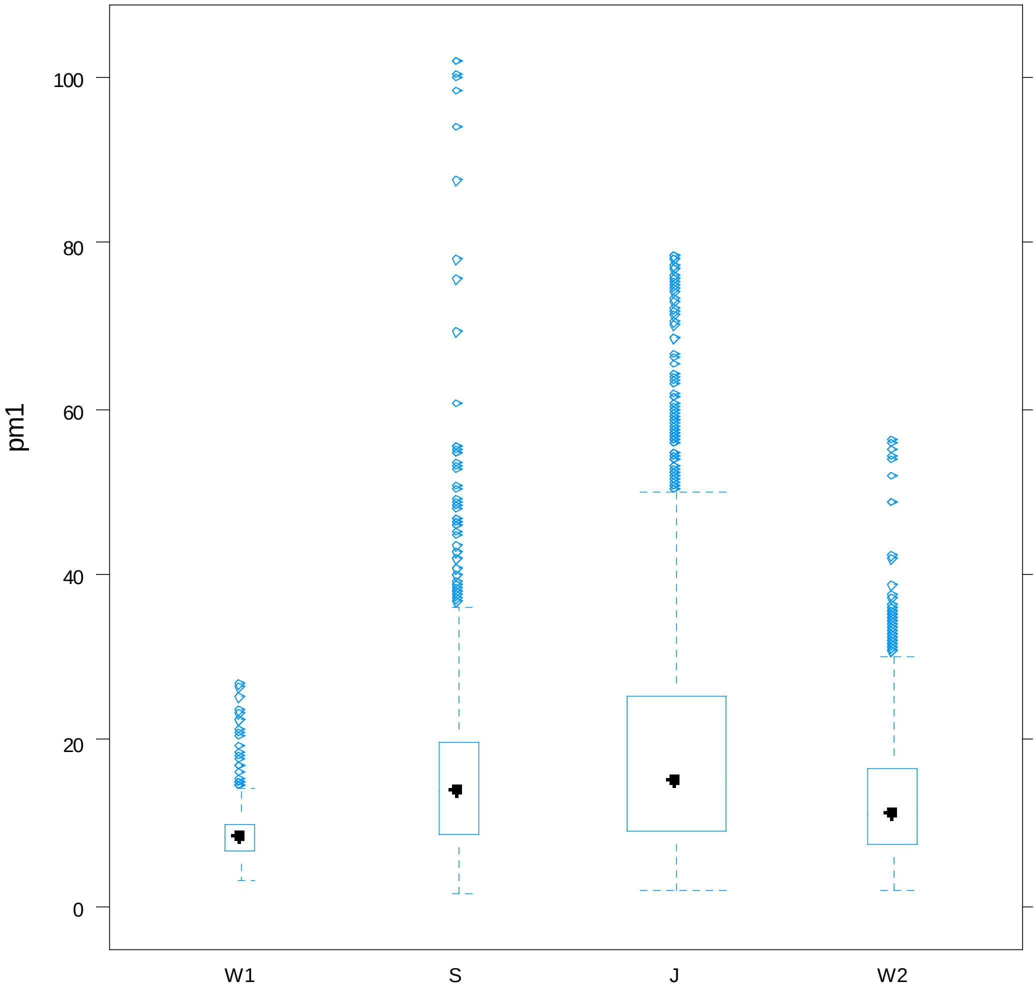


Figure 6.12 *Box and whisker plot showing the mean PM_1 exposure for bus segments*

6.2.1.4.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.23 Inter-*segment analysis of variance for* PM_1 *(logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	62.5749601	3	20.85832	275.26	**<0.05**
Within groups	934.69415	12335	.075775772		
Total	997.26911	12338	.080829074		

These results (Table 6.23) show that the overall model is statistically significant at p level <0.05. This means that the PM_1 level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.24).

Table 6.24 *Bonferroni matrix for the effect of bus segments on* PM_1 *exposure*

Row Mean – Col Mean	**J 18.17**	**S 16.62**	**W1 8.74**
S 16.62	**-2.08 p<0.05**		
W1 8.74	**-9.43 p<0.05**	**-7.88 p<0.05**	
W2 12.97	**-5.2 p<0.05**	**-3.65 p<0.05**	**4.23 p<0.05**

As is displayed by Table 6.24, the Bonferroni test yields significant differences between all group means at p<0.05.

6.2.1.4 Summary: Bus Inter-Segment Comparison

To summarise the results for the segment- comparison for the bus journey, the actual bus trip from ACBD to Mt. Albert was the highest for CO and PM_1. The exposures for PM_{10} and $PM_{2.5}$ were highest at the time spent at the bus stop .The difference in exposure between the bus ride and the bus stop was statistically significant for all pollutants except for PM_{10}. The maximum values for all the particulates were significantly higher at the bus stop compared to all other segments. The exposure levels at the bus stop and the journey exceeded the levels during both waiting periods for all the pollutants.

6.2.2 Car Journey

6.2.2.1 CO

6.2.2.1.1 Descriptive Statistics

Table 6.25 *Descriptive statistics for CO for car segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	3.61	3.54	3.67	3.00	1.26	14.20	1.43	6.14
J	7.97	7.91	8.03	7.43	2.59	29.35	2.85	38.10
CP	6.07	5.94	6.19	6.08	1.00	25.57	2.37	5.54
W2	4.83	4.60	5.05	4.27	2.72	9.85	1.93	1.14

The CO exposure was highest during the actual drive from the ACBD to Mt. Albert Road. This was followed by the CO level in the underground car park. The CO levels experienced during the waiting periods were significantly lower than both the journey and the time spent at the car park. Figure 6.13 displays the CO levels for each of the segment in sequential order.

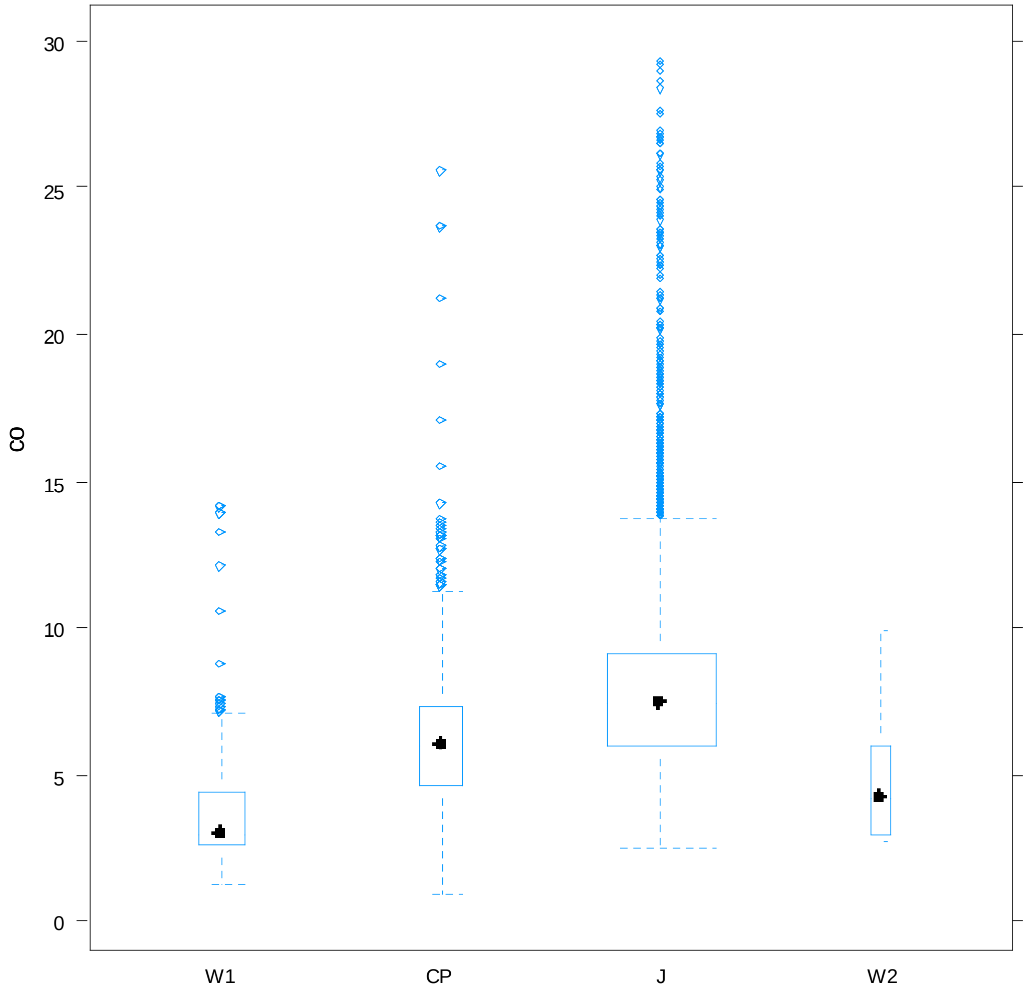


Figure 6.13 *Box and whisker plot showing the mean CO exposure for car segments*

6.2.2.1.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.26 *Inter-segment analysis of variance for CO (logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	192.688113	3	64.2293711	3164.75	**<0.05**
Within groups	262.336566	12926	.020295263		
Total	455.024679	12929	.035194112		

These results (Table 6.26) show that the overall model is statistically significant at p level <0.05. This means that the CO level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.27).

Table 6.27 *Bonferroni matrix for the effect of car segments on CO exposure*

Row Mean –Col Mean	CP 6.07	J 7.97	W1 3.61
J 7.97	1.9 $p<0.05$		
W1 3.61	-2.46 $p<0.05$	-4.36 $p<0.05$	
W2 4.83	-1.24 $p<0.05$	-3.14 $p<0.05$	1.22 $p<0.05$

As is displayed by Table 6.27, the Bonferroni test yields significant differences between all group means at $p<0.05$.

6.2.2.2 PM_{10}

6.2.2.2.1 Descriptive Statistics

Table 6.28 *Descriptive statistics for PM_{10} for car segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	24.76	22.86	26.66	21.40	8.30	229.70	16.47	6.14
J	23.50	23.14	23.86	18.90	5.40	151.20	16.20	38.10
CP	26.22	25.47	26.97	23.80	6.30	66.70	11.33	5.54
W2	23.61	21.16	26.06	22.55	10.10	38.90	8.63	1.14

Although the exposure did not vary greatly across the different segments for PM_{10} exposure levels, the underground car park was seen to be the most polluting micro-environment among all the segments. The lowest PM_{10} level was experienced during the journey between the ACBD and Mt. Albert. Figure 6.14 displays the PM_{10} levels for each of the segment in sequential order.

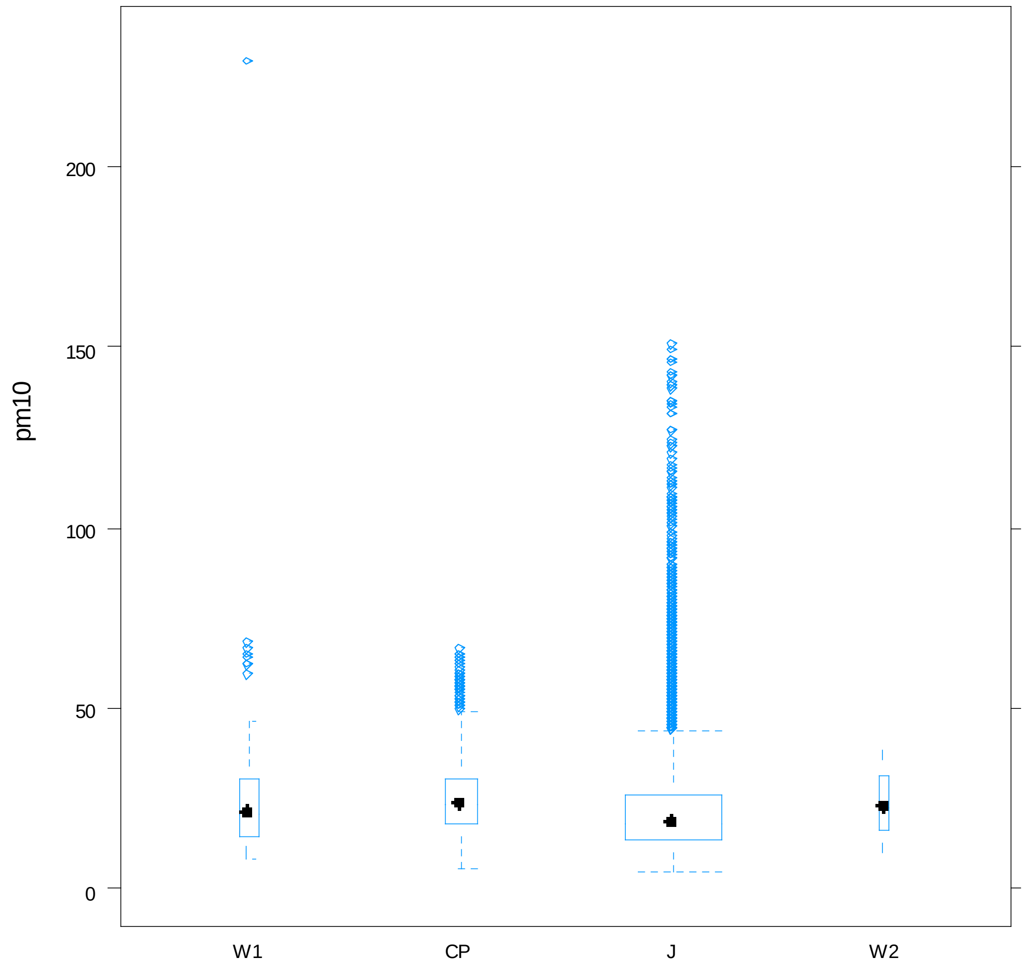


Figure 6.14 *Box and whisker plot showing the mean PM_{10} exposure for car segments*

6.2.2.2.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.29 *Inter-segment analysis of variance for PM_{10} (logged value)*

Source	**SS**	**df**	**MS**	**F**	**Prob >F**
Between Groups	4.59229307	3	1.53076436	33.41	**<0.05**
Within groups	418.008246	9124	.045814144		
Total	422.600539	9127	.046302239		

These results (Table 6.29) show that the overall model is statistically significant at p level <0.05. This means that the PM_{10} level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.30).

Table 6.30 *Bonferroni matrix for the effect of car segments on PM_{10} exposure*

Row Mean –Col Mean	**CP 26.22**	**J 23.50**	**W1 24.76**
J 23.50	**-2.72 p<0.05**		
W1 24.76	**-1.46 p=0.031**	**1.26 p=0.048**	
W2 23.61	-2.61 p=0.739	0.11 p=0.832	1.15 p=1

Table 6.30 displays the Bonferroni test results between the group means. No statistical difference was found between the final waiting period and any of the other segments. All other segments were significantly different from each other at p-value level of <0.05.

6.2.2.3 $PM_{2.5}$

6.2.2.3.1 Descriptive Statistics

Table 6.31 *Descriptive statistics for $PM_{2.5}$ car segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	13.93	13.12	14.73	11.90	5.70	41.60	7.00	6.14
J	18.62	18.29	18.96	13.90	4.74	144.40	15.26	38.10
CP	12.37	12.01	12.73	5.43	4.00	44.40	11.00	5.54
W2	15.34	13.82	16.86	14.70	8.87	24.10	5.36	1.14

Table 6.31 shows that the car trip from ACBD to Mt. Albert was the most polluting in terms of $PM_{2.5}$ exposure. Both the waiting periods had higher $PM_{2.5}$ levels than the underground car park. Figure 6.15 displays the $PM_{2.5}$ levels for each of the segment in sequential order.

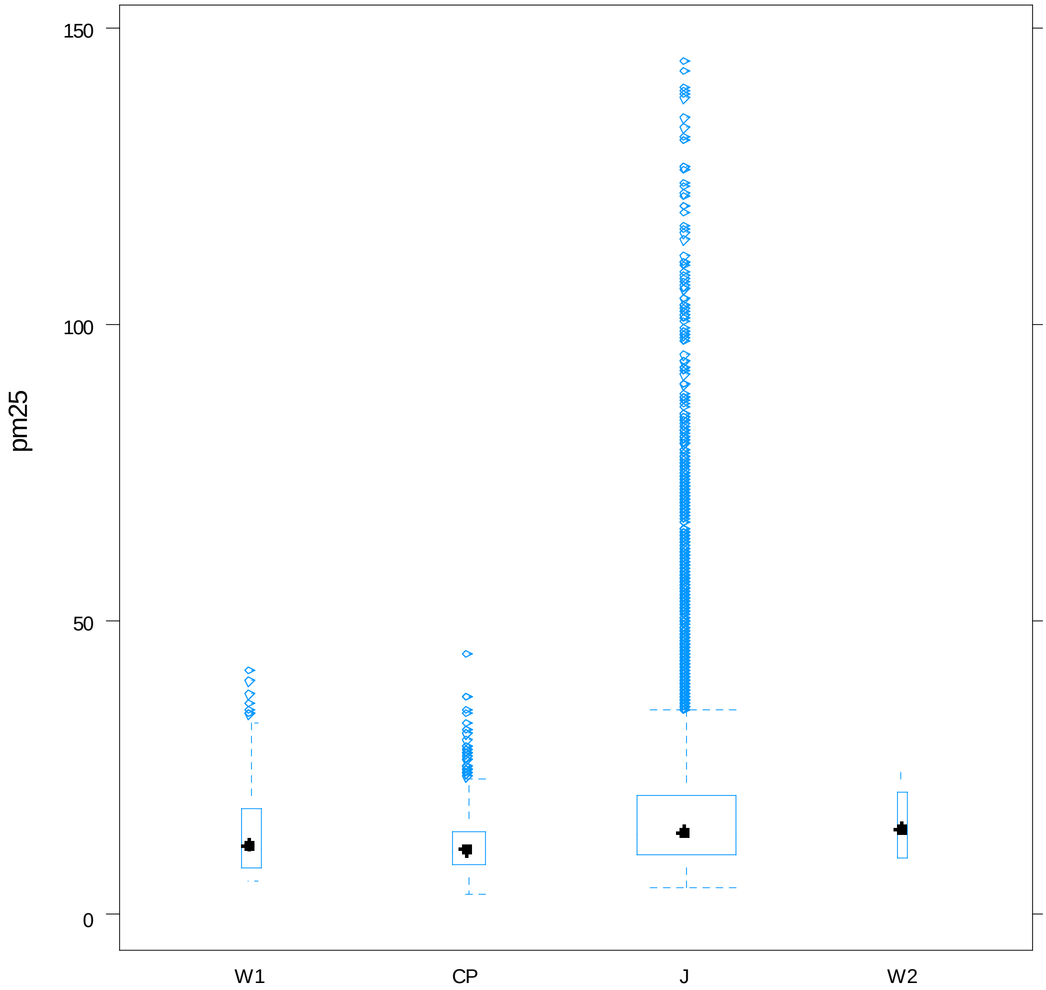


Figure 6.15 *Box and whisker plot showing the mean $PM_{2.5}$ exposure for car segments*

6.2.2.3.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.32 *Inter-segment analysis of variance for $PM_{2.5}$ (logged value)*

Source	SS	Df	MS	F	Prob >F
Between Groups	15.4565121	3	5.15217068	93.52	**<0.05**
Within groups	502.666386	9124	.055092765		
Total	518.122898	9127	.056768149		

These results (Table 6.32) show that the overall model is statistically significant at p level <0.05. This means that the $PM_{2.5}$ level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.33).

Table 6.33 *Bonferroni matrix for the effect of car segments on $PM_{2.5}$ exposure*

Row Mean –Col Mean	CP 12.37	J 18.62	W1 13.93
J 18.62	**6.25 p<0.05**		
W1 13.93	1.56 p=0.073	**-4.69 p<0.05**	
W2 15.34	**2.97 p=0.016**	-3.28 p=0.945	1.41 p=0.394

Table 6.33 displays the Bonferroni test results between the group means. No statistical difference was found between the first waiting period and the car park or the final waiting period. Similarly, no statistical difference resulted between the final waiting period and the journey.

6.2.2.4 PM_1

6.2.2.4.1 Descriptive Statistics

Table 6.34 *Descriptive statistics for PM_1 for car segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	6.81	6.40	7.22	6.80	1.70	22.30	3.53	6.14
J	14.60	14.26	14.93	9.40	1.70	141.80	15.22	38.10
CP	6.95	6.64	7.26	5.50	1.70	32.10	4.66	5.54
W2	9.40	8.19	10.60	7.17	5.53	18.40	4.24	1.14

As with the CO and $PM_{2.5}$ exposures, the car trip was the most polluting in terms of PM_1 exposure. The underground car park exposure was significantly lower compared to the trip exposure. Figure 6.16 displays the PM_1 levels for each of the segment in sequential order.

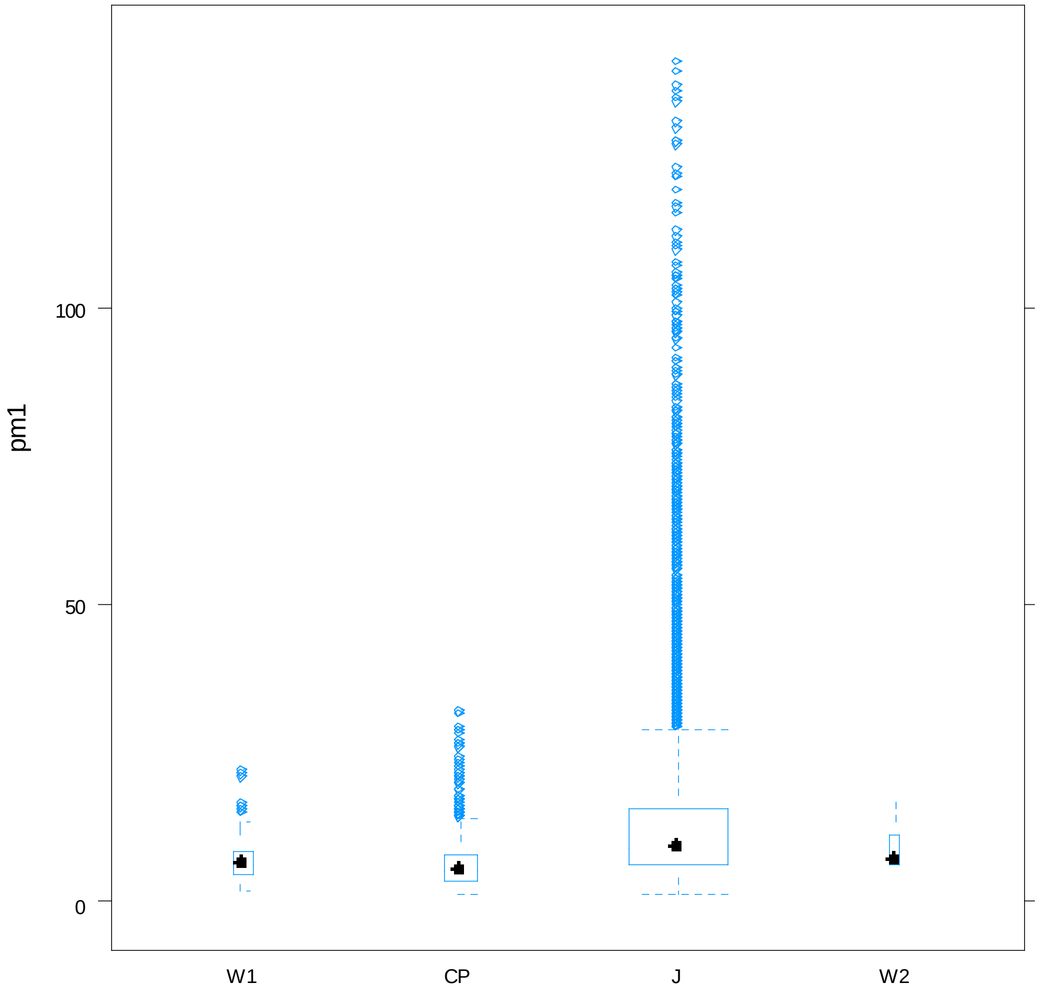


Figure 6.16 *Box and whisker plot showing the mean PM_1 exposure for car segments*

6.2.2.4.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.35 *Inter-segment analysis of variance for PM_1 (logged value)*

Source	**SS**	**Df**	**MS**	**F**	**Prob >F**
Between Groups	73.6928585	3	24.5642862	286.94	**<0.05**
Within groups	781.08755	9124	.085608017		
Total	854.780409	9127	.093654038		

These results (Table 6.35) show that the overall model is statistically significant at p level <0.05. This means that the PM_1 level for at least one of segments of the bus journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.36).

Table 6.36 *Bonferroni matrix for the effect of car segments on PM_1 exposure*

Row Mean –Col Mean	**CP 6.95**	**J 14.60**	**W1 6.81**
J 14.60	**7.65 p<0.05**		
W1 6.81	-0.04 p=1	**-7.79 p<0.05**	
W2 9.40	**2.45 p<0.05**	-5.20 p=0.093	**2.59 p=0.001**

Table 6.36 displays the Bonferroni test results between the group means. No statistical difference was found between the first waiting period and the car park. Similarly, no statistical difference resulted between the final waiting period and the journey.

6.2.2.5 Summary: Car Inter-Segment Comparison

The difference in exposure between the actual car ride and the car park was seen to be statistically significant for all four pollutants monitored. The journey had the highest levels for CO, $PM_{2.5}$ and PM_1, but the highest levels of PM_{10} was found in the underground car park. However, the car park had the lowest $PM_{2.5}$ level compared to all the other segments.

6.2.3 Train Journey

6.2.3.1 CO

6.2.3.1.1 Descriptive Statistics

Table 6.37 *Descriptive statistics for CO for train segments*

Segment	Mean	CI - 95%	CI 95%	Median	Min	Max	SD	Average Time(m)
W1	3.08	3.05	3.10	2.87	1.00	9.16	0.80	14.19
J	3.36	3.34	3.38	3.09	1.00	10.64	0.85	25.15
TS	3.78	3.71	3.86	3.20	1.82	7.08	1.37	5.05
BS	3.10	3.07	3.14	3.01	2.40	4.41	0.48	2.86
W2	3.22	3.18	3.25	3.10	1.04	7.92	0.72	3.54

Although there was very little variation in CO exposure across the different segments in the train journey, the outdoor train station was seen to be the most polluting micro-environment. The train ride from Britomart Station to the Mt. Albert Station had the second highest CO level. The exposure level inside the indoor station had lower CO levels than the train journey or the outdoor train station. Figure 6.17 displays the CO levels for each of the segment in sequential order.

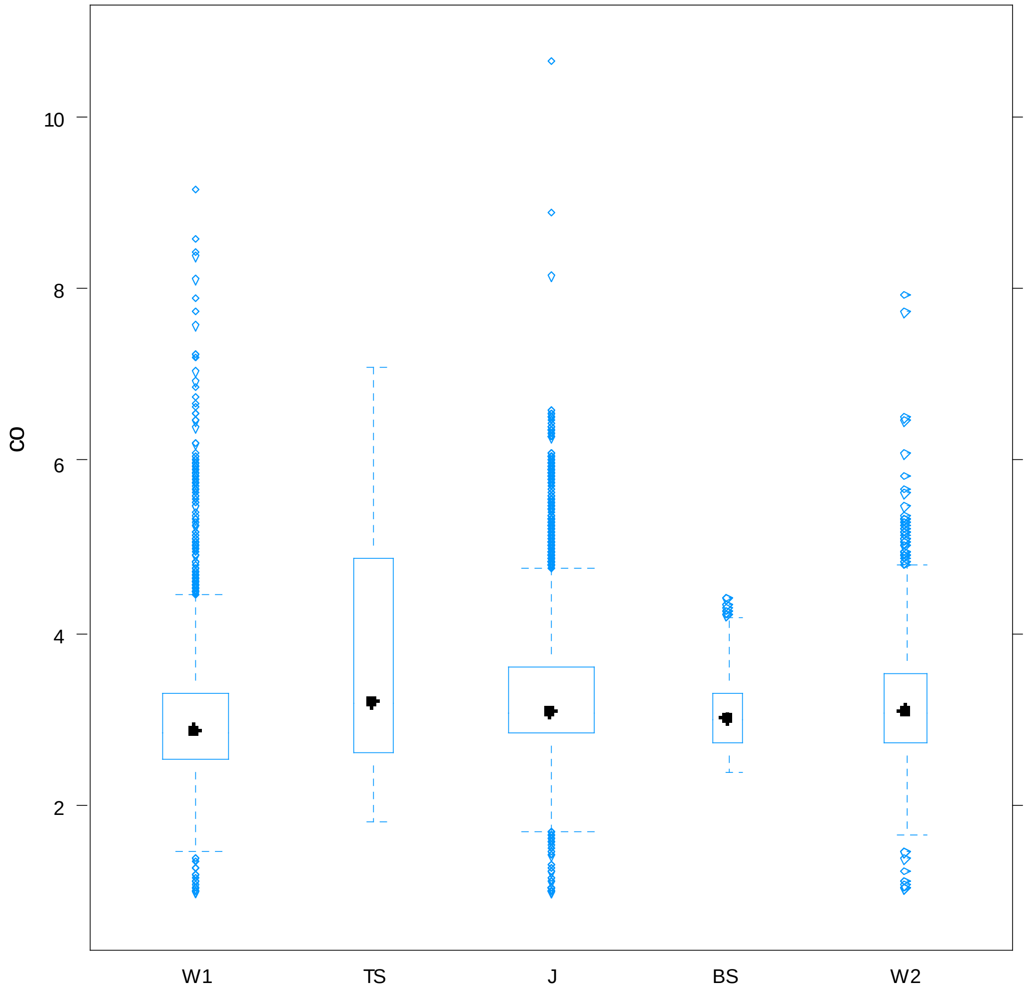


Figure 6.17 *Box and whisker plot showing the mean CO exposure for train segments*

6.2.3.1.2 Analysis of Variance and Post-Hoc Bonferroni Test

Table 6.38 *Inter-segment analysis of variance for CO (logged value)*

Source	**SS**	**Df**	**MS**	**F**	**Prob >F**
Between Groups	5.87473897	4	1.46868474	147.06	**<0.05**
Within groups	133.116014	13329	.009986947		
Total	138.990753	13333	.035194112		

These results (Table 6.38) show that the overall model is statistically significant at p level <0.05. This means that the CO level for at least one of segments of the train journey differs significantly from at least one other at the p-value level of <0.05. The statistical significance between each of the group means are displayed in the Bonferroni table below (Table 6.39).

Table 6.39 *Bonferroni Matrix for the effect of train segments on CO exposure*

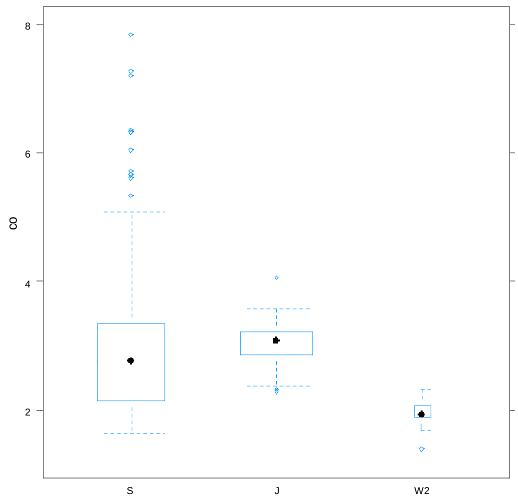
Row Mean –Col Mean	**BS 3.10**	**J 3.36**	**TS 3.78**	**W1 3.08**
J 3.36	**0.26 p<0.05**			
TS 3.78	**0.68 p<0.05**	**0.42 p<0.05**		
W1 3.08	-0.02 p=0.118	**-0.18 p<0.05**	**-0.60 p<0.05**	
W2 3.22	0.12 p=0.287	**-0.14 p<0.05**	**-0.56 p<0.05**	**0.14 p<0.05**

Table 6.39 displays the Bonferroni test results between the group means. No statistical difference was found between the two waiting periods and the indoor metro station.

6.3 Evidence of Elevated Exposures in Micro-Environments on Individual Journeys

This section includes examples of elevated exposures in transport micro-environments on individual journeys. As is evidenced by the figures below (Figures 6.18- 26) pollutant exposures reach elevated levels in micro-environments such as sheltered car parks, outdoor bus stops and train stations. More detailed explanation is included in the caption for each figure.

6.3.1 Elevated Exposure at Bus Stop



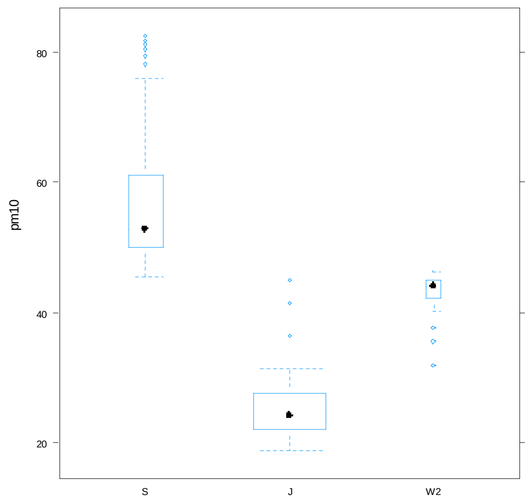
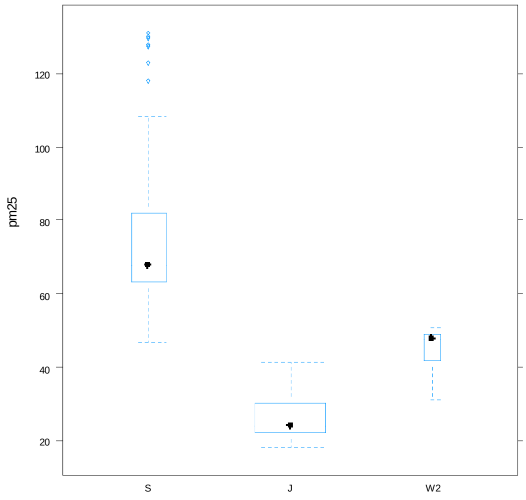


Figure 6.18 Elevated CO exposure in the outdoor bus stop. The elevated CO exposure at the bus stop exceeds the mean exposure during the overall journey Date: 28.04.2009 Time of day: PM Mean CO exposure: 3.50 ppm	**Figure 6.19** Elevated PM_{10} exposure in the outdoor bus stop. The elevated PM_{10} exposure at the bus stop exceeds the mean exposure during the overall journey Date: 28.04.2009 Time of day: PM Mean PM_{10} exposure: 23.50 μg^3



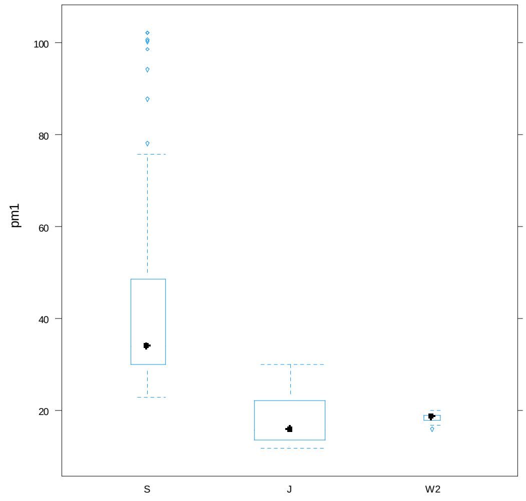
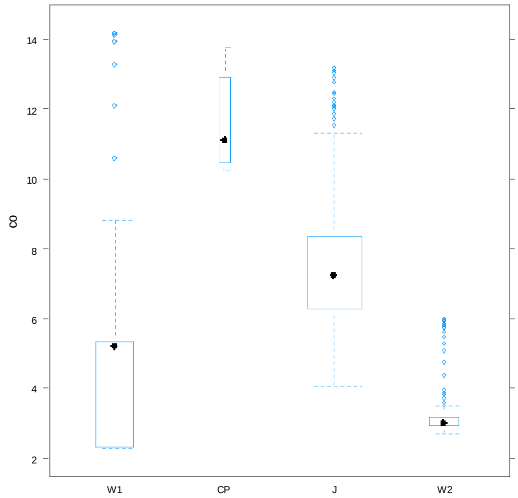


Figure 6.20 Elevated $PM_{2.5}$ exposure in the outdoor bus stop. The elevated $PM_{2.5}$ exposure at the bus stop exceeds the mean exposure during the overall journey Date: 28.04.2009 Time of day: PM Mean $PM_{2.5}$ exposure: 22.77 μg^3	**Figure 6.21** Elevated PM_1 exposure in the outdoor bus stop. The elevated PM_1 exposure at the bus stop exceeds the mean exposure during the overall journey Date: 28.04.2009 Time of day: PM Mean PM_1 exposure: 16.62 μg^3

6.3.2 Elevated Exposure in Underground Car Park



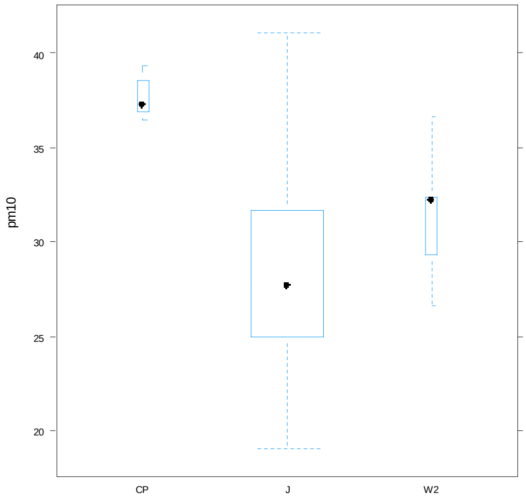
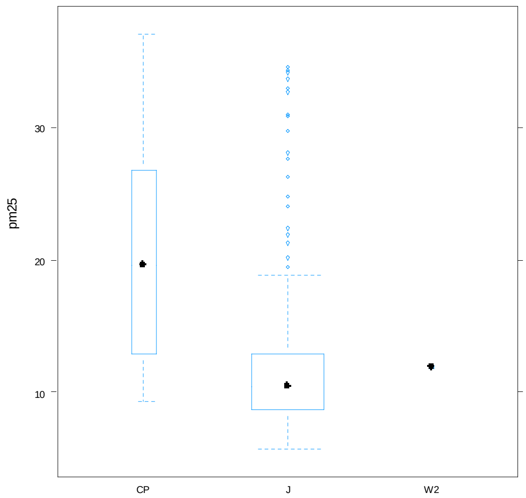


Figure 6.22 Elevated CO exposure in the underground car park. The elevated CO exposure at the car park exceeds the mean exposure during the overall journey Date: 29.04.2009 Time of day: PM Mean CO exposure: 7.11 ppm	**Figure 6.23** Elevated PM_{10} exposure in the underground car park. The elevated PM_{10} exposure at the car park exceeds the mean exposure during the overall journey Date: 28.04.2009 Time of day: PM Mean PM_{10} exposure: 23.80 μg^3



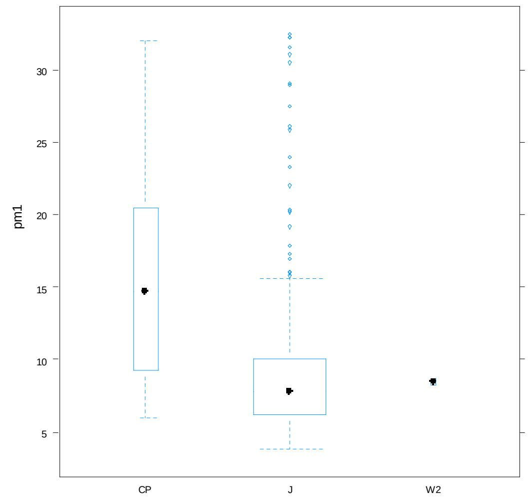


Figure 6.24
Elevated $PM_{2.5}$ exposure in the underground car park. The elevated $PM_{2.5}$ exposure at the car park exceeds the mean exposure during the overall journey

Date: 30.04.2009
Time of day: PM
Mean $PM_{2.5}$ exposure: 17.85 μg^3

Figure 6.25
Elevated PM_1 exposure in the underground car park. The elevated PM_1 exposure at the car park exceeds the mean exposure during the overall journey

Date: 28.04.2009
Time of day: PM
Mean PM_1 exposure: 13.29 μg^3

6.3.3 Peak Exposure in Outdoor Train Station

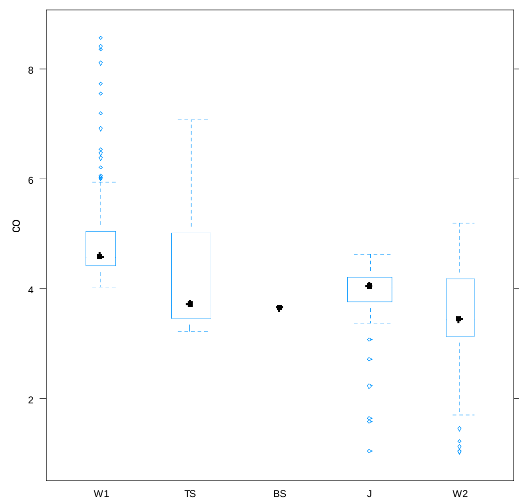


Figure 6.26

Elevated CO at the outdoor train station. The elevated CO exposure at the train station exceeds the mean exposure during the overall journey

Date: 13.05.2009
Time of day: PM
Mean CO exposure: 3.20 ppm

6.3.4 Summary

Exposures in certain micro-environments, namely the underground car park, the outdoor bus stop and the outdoor train station greatly exceeded the mean exposures for the entire journey. No CO peaks were present in the indoor metro station.

6.4Other factors

This section will present the results for the effects of wind speed and time of day on pollution exposure.

6.4.1 Wind Speed

6.4.1.1 Descriptive Statistics

Table 6.40 *Descriptive statistics for high and low wind speed on overall pollution level*

Speed	**CO Mean**	**CO SD**	**PM_{10} Mean**	**PM_{10} SD**	**$PM_{2.5}$ Mean**	**$PM_{2.5}$ SD**	**PM_1 Mean**	**PM_1 SD**
High	4.30	2.45	24.32	27.84	18.00	19.21	12.11	10.94
Low	5.03	3.01	24.68	12.74	20.78	13.33	16.00	12.66
All Groups	4.55	2.68	24.45	23.61	18.98	17.40	13.49	11.73

Low wind speed was a precursor for higher levels of pollutant across all five pollutants (Table 6.40). Table 6.41, which presents the t-test results for the low and high wind comparison, shows that the difference in pollutant levels resulting from different wind speeds is significant at the level $p<0.05$ except for $PM_{10.}$

6.4.1.2 T-test Comparison

Table 6.41 *T-test results for effect of high and low wind speed on overall pollution level*

Pollutant	Mean High	Mean Low	df	p
CO	4.30	5.03	55665	**$p<0.05$**
PM_{10}	24.32	24.62	21388	$p=0.19$
$PM_{2.5}$	18.00	20.78	21388	**$p<0.05$**
PM_1	12.11	16.00	21388	**$p<0.05$**

6.4.2 Time of Day

6.4.2.1 Descriptive Statistics

Table 6.42 *Descriptive statistics for effect of time of day on overall pollution level*

Time of Day	CO Mean	CO SD	PM_{10} Mean	PM_{10} SD	$PM_{2.5}$ Mean	$PM_{2.5}$ SD	PM_1 Mean	PM_1 SD
PM	4.34	2.51	23.56	23.01	17.29	13.20	12.27	11.93
AM	4.87	2.90	25.88	24.50	21.74	22.35	15.46	11.11
All Groups	4.55	2.68	24.45	23.61	18.98	17.40	13.49	11.73

Table 6.42 shows that higher levels of pollution across all five pollutants were experienced in the morning journeys when compared to afternoon trips.

6.4.2.2 T-Test Comparison

Table 6.43 *T-test results for effect of time of day on overall pollution level*

Pollutant	Mean PM	Mean AM	df	P
CO	4.34	4.87	55665	**$p<0.05$**
PM_{10}	23.56	25.88	33145	**$p<0.05$**
$PM_{2.5}$	17.29	22.35	33145	**$p<0.05$**
PM_1	12.27	15.46	33145	**$p<0.05$**

Table 6.43, which presents the t-test results for the comparison between pollutant levels on morning and afternoon journeys, shows that the difference in pollutant levels resulting from different wind speeds is significant at the level $p<0.05$.

6.4.3 Summary: Other Factors

Both wind speed and time of day were significant factors that influenced pollution levels. Low wind speed resulted in significantly higher pollution levels across all the monitored pollutants except for PM_{10}. Similarly, the pollution levels were higher for all five pollutants during the morning journeys compared to the afternoon ones.

CHAPTER SEVEN

Discussion

7.0 Introduction

Exposure to traffic pollution has become an increasing concern to the public. A number of studies have demonstrated that the air people breathe in while in transportation is particularly unsafe due to the high concentrations of CO, suspended particles ($PM_{10,}$ $PM_{2.5}$ and PM_1) and UFPs (Georgoilis et al., 2002; Kuo et al., 2000). Some studies have suggested that peak exposures of approximately one hour- a typical time spent in a transport micro-environment- may have more damaging health effects than the 24- hour sampling times current standards apply to (Michaels, 1996; Michaels and Kleinman, 2000). Despite the widespread interest in health effects from exposure to traffic pollutants, there is a distinct lack of research of this kind in New Zealand. Since it is essential to consider local conditions when carrying out pollution exposure studies, it is not wholly possible to reliably extrapolate results from other climates and countries to New Zealand. This research was carried out to assess the exposure to traffic pollution on different modes of transport. In addition to the inter-modal comparison, this project also aimed to identify and study how exposure varies on a single journey, and how certain micro-environments affect personal exposure. Key findings are discussed in this chapter. Section 7.1 will investigate the results from the inter- modal comparison. Section 7.2 will present the discussion for the pollution exposure in different micro-environments, namely the outdoor and indoor bus stops, the sheltered and underground car parks, outdoor train station and the underground metro station. Finally, the affect of other factors on personal exposure to pollution levels will be discussed in Section 7.3. These include meteorological conditions and commuting time of day.

7.1 Inter-modal Comparison

Exposure concentrations varied largely within and between different transport modes for the different pollutants. Various factors influence the exposure concentrations experienced by commuters traveling through the transport micro-environment on a particular mode of transport (Kaur et al., 2007). These can be broadly classified into four categories: personal factors, mode of transport factors, traffic factors and meteorological factors. Each of these categories, however, is influenced by an underlying spatial and/or temporal dependency which inadvertently influences personal pollution exposure levels (Kaur et al., 2007). In urban transport micro-environments, the spatial scale ranges from meters to kilometers and the temporal scale from minutes to several hours. This results in varying pollutant levels, depending upon location and activities taking place, and different exposures at different periods influenced by the length and instance in time spent in a particular part of the transport micro- environment. Kaur et al. (2007) reported that the mode of transport influences commuters' exposures at two levels: firstly, by the choice of transport used to move around, and secondly, the features and characteristics within each mode.

7.1.1 CO

Several studies have identified exposures in the transport micro-environment to be dependent on the mode of transport utilised (Dor et al., 1995; Rank et al., 2001). Duci et al. (2005) and Kaur and Nieuwenhuijsen (2009) reported that the mode of transport was a significant determinant of personal exposure to CO. High exposure concentrations experienced inside vehicles are common in earlier vehicle exposure studies. Chan et al. (1991) measured in-vehicle mean concentration to be 11.3 ppm; likewise, Liu et al. (1994) observed the mean CO concentration in a private car to be 11.0 ppm in Taipei, Taiwan. Georgoulis et al. (2002) reported much similar results for CO exposures inside cars across Europe, with concentrations varying between 1.24 ppm to 4.17 ppm. A study (Fernandez- Bremauntz and Ashmore, 1995), which measured CO concentrations in different transport modes, found that the highest concentrations were present in private cars. The same result was derived for this study, with the car driver having the highest concentrations of CO exposure in both Christchurch (4.1 ppm) and Auckland (7.1 ppm). Though the mean concentrations for CO were comparatively lower for New Zealand, compared to exposures in other cities in most cases, (Koushki et al., 1992; Ott et al., 1994), the maximum CO concentration experienced for both cities exceeded 29 ppm. This value exceeds the ambient guideline for CO outlined by NES (Appendix A). Such high maximum CO levels could be attributed to the fact that monitoring included the entire journey, including the time spent at the underground and sheltered car parks, which, in some instances, had very high CO levels. There are a number of potential explanations as to why CO levels are significantly higher in cars compared to other modes. Some authors have suggested that the higher levels can be attributed to the car traveling in a "tunnel of pollutants", as the main intake to a car is from the roadway traffic where there is a high concentration of these pollutants originating from the exhaust of all the vehicles on the road (Chan et al., 1993; Chertok et al., 2004). Clifford et al. (1997) reported that the in-vehicle concentration levels can be significantly influenced by the presence of a "dirty" vehicle in front, and Rodes et al. (1998) indicated that the vehicle in front could be responsible for a large proportion of the in-vehicle concentration. A study conducted to assess the effect of different ventilation modes on in-vehicle CO exposure (Esber et al., 2007), found that CO concentrations in cars with closed windows and vents on fresh air intake resulted in levels of CO as high as 75 ppm on a single journey. Chan et al. (2002b) found ventilation to be a crucial factor influencing in- vehicle pollutant levels. During the entire experiment, the car was driven with the windows closed, and the vents opened. Since the experiments were conducted during rush- hour traffic with expected maximum traffic volumes, there would have been a very high chance of pollutants entering the car through the open vents. Direct contamination form the motor vehicle itself can also lead to higher CO levels in cars (Lofgren et al., 1991; Duffy and Nelson, 1997; Leung and Harrison, 1999). Such self-pollution can occur when the vehicle's own emissions originating from fuel leaks and combustion byproducts enters the cabin through vents (Wohrnschimmel et al., 2008).

Cyclist CO exposure measurements are far less common compared to studies focused on other modes of transport (Kaur et al., 2007). For this study, the cyclists in Christchurch were exposed to the lowest level of CO. Although the on-road cyclist had a higher level of CO (2.96 ppm) compared to the off-road cyclist (2.67 ppm), and the analysis showed the the difference was statistically significant (Section 5.1.1.1), it was marginal. In Auckland however, the cyclist had the second highest exposure to CO (4.58 ppm). These levels for cyclists are slightly higher in New Zealand compared to other cyclists in other parts of the world, especially in Europe. For example, van Winjen et al. (1991) recorded mean CO exposure concentrations varying between 1.3 and 2.7 ppm for cyclists commuting along an inner city route around Amsterdam, The Netherlands. Similarly, Georgoulis et al. (2002) reported geometric mean concentrations to vary between 0.53-2.43 ppm for cyclists in Helsinki (Finland), Basel (Switzerland), Prague (Czech Republic), Athens (Greece) and Milan (Italy) in ascending order. An abundance of cycle lanes in Europe, which separates the cyclists from the on-road vehicles, may be a reason for the comparatively lower exposures in Europe. While examining the difference in exposures between Auckland and Christchurch cyclists, the lower levels for CO for the cyclists in Christchurch could be attributed to the fact that the cyclists were further away from the source of pollution i.e., the traffic. This would have allowed them to avoid or move through congested traffic. Furthermore, the cyclists were consistently next to the curb where pedestrians walk, unlike the vehicle drivers and passengers who are in the direct path of emissions. The inter-modal result for CO pollution in Auckland (Section 6.1.1.1) shows that the cyclist was exposed to a significantly higher levels of CO compared to the bus and train commuters. The consistently higher CO levels for all modes in Auckland, compared to Christchurch, could be attributed to the fact that Auckland has a higher traffic volume at peak times than Christchurch. Furthermore, due to a distinct lack of a cycle lane on the majority of the route in Auckland meant that the cyclist would have been more likely to be stuck in traffic jams, idle at traffic lights and weave through the traffic, thus greatly increasing the exposure levels to CO. This potentially explains why the maximum value for the cyclist CO level in Auckland was 115.15 ppm, which was almost four times higher than the maximum level experienced by the car driver.

While, the level of CO experienced in the bus was higher than for both the off- and on-road cyclist in Christchurch (3.07 ppm), it was lower than the cyclist exposure level in Auckland (3.50 ppm). Studies done in the past have reported levels of CO exposure in buses to be both higher and lower in concentration than those observed in New Zealand have. For exampled, Liu et al. (1994) measured the personal exposure to CO on the bus in Taipei, Taiwan and found that the mean exposure to be 11.6 ppm. In Mexico, Fernandez-Bremauntz and Ashmore (1995) noted that CO exposure varied between 12.9 and 59.4 ppm. In contrast, Han et al. (2005) reported that the mean CO personal exposure was 0.58 ppm during peak times in Leeds, UK. The significantly lower CO level in the more recent study done in England could be attributed to the 'rapidly declining CO emissions of cars and buses leading to decreasing street concentrations, particularly in North America and Western Europe' (Kaur et al., p.4797).

Bus commuters in both cities had CO exposure levels lower than the car driver could be attributed to the fact that the height of the intake point for buses is much higher than it is for cars, thus reducing the penetration of emissions from surrounding traffic compared to cars. Concerning comparisons to cyclists, the bus commuter had a higher CO level exposure in Christchurch, but lower in Auckland. This could be because in Christchurch, the cyclists rode the cycles along side the traffic, instead of having to be confined to the traffic flow, as was the case with the Auckland cyclist.

The train had the lowest CO level compared to all other modes monitored in Auckland. This is consistent with previous research carried out which showed that exposure levels obtained for railway transport was much lower than for other modes of transport (Chan et al., 2002; Chertok et al., 2004). For example, a study carried out in an urban area in China found that the average CO levels in roadway transports were 2.6- 9.3 times higher than that in the subway (Chan et al., 2002). Such lower pollution exposure level in rail transport in Auckland could be attributed to the fact that the commuting trains ran on its own underground track, which was located away from busy roads or other vehicular traffic emissions on the street. This meant that the train was not directly influenced by traffic pollution from the street.

7.1.2 Particulate Matter

7.1.2.1 PM_{10}

As mentioned before (Section 2.3.3), PM_{10} particles are less than 10 microns in diameter. PM_{10} pollution includes particles referred to as 'coarse' (between 2.5 and 10 microns) and 'fine' (less than 2.5 microns, also known as $PM_{2.5}$). These particulates are produced by combustion of fossil fuels. Road traffic is a significant source of PM_{10} particulates and about 73 percent of PM_{10} particulates originate from diesel exhaust alone (Auckland Regional Council, 2006b). These particulates do not just come from human sources- natural sources such as dust, pollen, sea salt and soil particles can also contribute to $PM_{10.}$

While examining the PM_{10} pollution across different modes in Christchurch, the bus commuter was exposed to the highest level (43.26 μg^3) compared to all the other modes. The on- road cyclist had the lowest PM_{10} exposure, and the off road cyclist had a slightly higher exposure than the car driver did. Though not all studies agree, the result from this research is comparable to those obtained by a number of commuter studies done over seas. For example, Chan et al. (2002) found the average PM_{10} to be the highest in a non-air conditioned bus (203 μg^3). The very high value in the Chinese metropolis could be attributed to the growing traffic volume and density in China (Jingsong, 2003). There could be several reasons for the comparably high exposure levels on the bus compared to other modes. Buses usually travel near the curb-side of the road, where stop-and-go traffic is relatively common. The bus- stop at the University of Canterbury services more than five other bus-serviced routes, which meant than quite often the measured bus, as well as other serviced buses required to queue up when approaching the bus stop. In addition, they are also required to halt several minutes at bus stops for passenger boarding and dropping off. Because of the close proximity of the buses, the emission from the front bus could have easily penetrated into the bus behind it during idling at intermediate stops. Such impact was one of the possible causes of higher PM_{10} values.

Buses in New Zealand did not have dedicated bus lanes at the time of monitoring. Because of this, they most likely received direct emissions from exhaust pipes of gas-powered vehicles idling or accelerating in front of them (Wohrnschimmel et al., 2008). Furthermore, the majority of buses are not air conditioned in Christchurch (Metroinfo, 2009). This meant that the bus windows were left open, which increased the penetration of the pollutant in the bus compartment thus elevating the PM_{10} level inside buses, especially during stop-and-go traffic (Chan et al., 2002). Aside from external sources such as vehicle exhaust, the PM_{10} level could also be affected by an internal PM_{10} source (Chan et al., 2002). The re-suspension of dust from the vehicle floor due to passenger movement could also considerably increase PM_{10} levels (Praml and Schierl, 2000). Therefore, frequent passenger movement in buses could be another cause of higher internal PM_{10} source. Concerning the inter-modal PM_{10} exposure comparisons in Auckland, the bus commuter was exposed to lower levels compared to the cyclist and the car driver. One possible explanation is that fewer buses frequented the Auckland bus stop, this reducing the build-up of idling buses. Additionally, there were fewer bus stops along the route in Auckland, thus significantly reducing the number of stop-and-go movements.

In both Christchurch and Auckland, the car driver was exposed to relatively low levels of PM_{10} (36.74 μg^3 and 23.80 μg^3 respectively). While in Christchurch, the levels experienced were lower than those experienced by both the bus commuter and the off-road cyclist and only slightly higher than the level for on-road cyclist, in Auckland, the PM_{10} level in the car was significantly lower than the level experienced by the cyclist and only marginally lower than that in the bus. The reason for this could be that the closed window condition in the car separated the vehicle interior air from the roadway air, thus preventing direct entrance of the tailpipe emissions from the neighbouring vehicles into their compartments from the open windows. Additionally, part of the coarse sizes PM_{10} might be filtered from the air stream by filter during fresh air intaking in these vehicles (Chan et al., 2002). As Briggs et al. (2008, p.12) explain, the filtration system possibly prevents the ingress if particles, making the vehicle a “more- or- less independent micro-environment, insulated against much of the particulate air pollution present in the street”.

While examining the cyclists' exposure to PM_{10} levels in both cities, some conflicting results surfaced. While the on-road cyclist in Christchurch had the lowest exposure to the pollutant (32. 46 μg^3), the cyclist in Auckland had the highest exposure (25.94 μg^3). This could again be attributed to the fact that while the cyclist in Christchurch rode the bike alongside the traffic on a cycle lane, the Auckland cyclist was in direct line of emissions from surrounding traffic. Furthermore, the cyclist was not protected from the pollutants by a shield of the vehicle, as in the case of the bus and car commuters. The cyclist experienced extremely high PM_{10} levels of over 1000 μg^3 (Figure 6.4 in Section 6.1.2.1). The off-road cyclist in Christchurch had a much higher PM_{10} level than the on-road cyclist or the car commuter. It is important to note that the off- road cyclist followed a route through Hagley Park about five meters away from the road. The particulates exposed to the off-road cyclist were most likely not particles emitted from vehicle emissions, but rather pollen from the surrounding vegetation, and dry dust from the soil where the vegetation was planted. Furthermore, the off-road cyclist had to share the path with other users such as the pedestrians and joggers. Their frequent movement along the route could have been responsible for the high levels of PM_{10} experienced by the off-road cyclist. One important point to note is that the comparison between the car driver exposure and the off- road cyclist was shown to be statistically insignificant. One reason for this could be that, although the off- road cyclist had a much higher mean PM_{10} level than the car driver, both experienced approximately the same range (4.30- 573 μg^3 and 10.80- 515.80 μg^3 respectively) of particulate exposure.

All modes in Christchurch were exposed to consistently higher PM_{10} levels compared to the Auckland modes. This could be explained by the fact that major construction work was taking place at the centre of town in Christchurch (Section 5.2.1.2). The commuters would have been exposed to the particulates originating from the construction site while they waited for about twenty minutes at the centre of town. Breghmans et al. (2008) identified both mechanical and manual construction work to be a strong source of $PM_{10.}$ The different exposure levels for traffic pollutants in the two cities could also have arisen because of differences in topography or due to ambient background levels and meteorology at the time of monitoring. Previous research has shown these factors to significantly affect pollution levels (Bevan et al., 1991; Holmes et al., 2005). However, since the ambient background concentrations or the affect of topography on pollution levels were not part of the research objectives, these factors were not taken into account.

7.1.2.2 $PM_{2.5}$

$PM_{2.5}$ particles represent particulates smaller than 2.5 microns in diameter. Most $PM_{2.5}$ particles originate from combustion sources, whereas PM_{10} particles include natural particles such as sea salt and soil, which are largely absent from $PM_{2.5}$ (Ministry for the Environment, 2007). While examining the $PM_{2.5}$ exposures across the different modes, the bus commuter was exposed to the highest level of $PM_{2.5}$ in both cities (22.88 μg^3 in Christchurch, and 22.77 μg^3 in Auckland). The exposure $PM_{2.5}$ levels for buses are variable across different countries. A study done in Mexico found the $PM_{2.5}$ levels to be three times higher than those in New Zealand (Gomez- Peralez et al., 2004). Similarly, Chan et al. (2002) found $PM_{2.5}$ levels to be 97 μg^3 in an urban city in China. A study conducted in Taipei, Taiwan (Tsai et al., 2008) found that bus commuters were exposed to higher levels of $PM_{2.5}$ than those who traveled in cars. High exposures in buses could be related to the fact the bus commuters are potentially exposed to $PM_{2.5}$ emitted from vehicles while they are waiting at the roadside bus stop. Additionally, as with the PM_{10} exposures, the $PM_{2.5}$ particles could have potentially entered through the open windows in the non-air conditioned buses. Additionally, the frequent stop-and-go motion of the buses would have allowed vehicle emissions from surrounding vehicles to enter the bus compartment. Chan et al. (2002) found that instantaneous and obvious concentration peaks were usually observed in the stop-and-go patterns. The $PM_{2.5}$ concentrations in car were seen to be much lower than the bus concentrations in both Christchurch (17.13 μg^3) and Auckland (17.85 μg^3). Although higher exposures were found in cars in the particular study, comparable inter-modal results were obtained in Guangzhou, China (Chan et al., 2002). Lower levels in the car, compared to buses, could have resulted from the fact that, unlike buses, cars usually traverse in the middle of the road with a faster running speed and lower traffic density (Chan et al., 2002). In the middle of the lane, the increased air turbulence due to the increased speed in the car could have helped to increase the dispersion of the emission exhaust and lower pollutant levels.

While comparing the cyclist exposure to the car driver exposure, it was found that both on- and off-road cyclists had higher $PM_{2.5}$ levels compared to the car driver in Christchurch. The off- road cyclist had a comparatively higher $PM_{2.5}$ exposure than the car driver did, as opposed to the on- road cyclist whose mean exposure was only 0.01 μg^3 more than the car driver's. These results conflicted with previous results published. For example, a study carried out in 11 Dutch cities found that the overall mean concentration of $PM_{2.5}$ in the car was 11% higher than during the cycling. Other studies have reported similar inter-modal comparison results between cars and cycles (Kingham et al., 1998; Rank et al., 2001; Adams et al., 2002). The results from Auckland; however, correlated very well with the evidence from international literature: the cyclist had significantly lower $PM_{2.5}$ levels compared to the commuters traveling in the car and bus. The comparatively high levels of $PM_{2.5}$ for the off-road cyclist could possibly be explained by the fact that for $PM_{2.5}$, long-range distance transport results in a high background concentration (Boogarde et al., 2009), which could have potentially increased the level $PM_{2.5}$ for the off- road cyclist even though the cyclist was not in the direct line of traffic emissions. Even though the cyclist in Auckland had the lowest mean $PM_{2.5}$ exposure, the maximum level he experienced (represented as an outlier in the box and whisker plot in Figure 6.6) was much higher than the maximum levels for the other modes. This could be explained by the fact that the cyclist had to maneuver through rush-hour traffic, thus being exposed to very high levels of $PM_{2.5}$ during the commute.

7.1.2.3 PM_1

PM_1 particulates consist of ambient fine particulates with a diameter of less than one micron. As has been established before (Section 2.3.4), fine particles in urban areas arise mainly from the gas-to-particle conversion processes within the atmosphere, or from secondary anthropogenic combustion products originating mainly from vehicular traffic (Hildemann et al., 1991; Schauer et al., 1996; Kleenman and Cass, 1998). Studies comparing PM exposures on different modes of transport have predominantly focused on PM_{10} and $PM_{2.5}$. A study carried out in London (Briggs et al., 2008) compared PM_1 exposures whilst simultaneously walking and driving in London. The results showed that exposures while walking are greatly in excess of those while driving, by a factor of 2.2 for $PM_{1.}$ The lower exposures in the car could be attributed to the filtration system which prevents the particles into the car. The additional time involved in walking also increases the PM_1 levels for pedestrians. This could be attributed to the increased dosage rate of experienced while walking (Gulliver and Briggs, 2008), which could have lead to increased absorption rates compared to car drivers (McNabola, 2008).

While examining the results from this study, it was seen that PM_1 levels were highest in the bus in both Christchurch and Auckland. This could be attributed to the fact that buses have to stop frequently to allow passengers to get on board, and PM_x exposures have been known to be high for stop-and-go traffic movements. Furthermore, the fact that these buses used diesel as the choice of fuel could have great increased the PM level since, diesel vehicles can contribute a significant amount of particulate matter in the air (Ministry for the Environment, 2007). This could have also increased the PM_1 levels inside as the bus emissions could have entered the compartment during the opening and closing of doors. The mode that had the second highest PM_1 exposure was car in both cities (9.43 μg^3 in Christchurch, 13.29 μg^3 in Auckland). Although in Christchurch, the on- road cyclist had a marginally higher PM_1 exposure (9.53 μg^3), statistical analysis showed the relationship between the car and the on-road cyclist to be insignificant. This could have resulted because of the very similar range of PM_1 exposure between the two modes (1.90- 55.90 μg^3 for car, and 0.92- 51.70 μg^3 for on- road cycle). The off- road cyclist had the lowest PM_1 exposure levels. Since the off-road cyclist was away from the road, he would have been able to avoid the originating PM_1 from the vehicle emissions, but not for coarser fractions. It is also important to note that although the off- road cyclist had the lowest mean PM_1 exposure, the exposure was very extreme in some cases (expressed as outliers in Figure 5.8). This could be attributed to the fine soil particles from Hagley Park, which the off- road cyclist rode through. Similarly, in Auckland, the cyclist also had the lowest levels of PM_1 but was also exposed to very high values of

PM_1. Such high values could have resulted from the dual effect of Auckland having very high traffic density at peak hours and the cyclist having to weave through the heavy traffic. It is very important to realise that the influence of time- activity and movement can be easily missed by using averaged results, leading to underestimation of exposures (Morawaska et al., 2008).

7.1.3 Ultrafine Particles (UFPs)

Ultrafine particles (UFPs) are defined as those with diameters less than 0.1 microns. Though they are abundant in number, they contribute little to mass (Donaldson et al., 1998; Penttiten et al., 2001). Current research shows that exposure to UFPs could have very significant health effects. Because of their small size, UFPs can penetrate the respiratory system more efficiently, and even transfer to the extrapulmonary organs, including the central nervous system (Hagler, 2009). UFPs have also been shown to have stronger associations with respiratory and cardiovacscular health than $PM_{2.5}$ particulates (Hagler, 2009). In urban environments, the dominant sources of ultrafine particles are direct emissions from motor vehicles and secondary particles are generated by the photochemical or physical processes in the atmosphere (Fine et al., 2004; Zhang et al., 2004). As with this research, an experiment done in London (Kaur and Nieuwenhuijsen, 2009) found the mode of transport to be a statistically significant determinant of UFP exposure. The same study showed the UFP exposure in a car to be slightly higher than the exposure in a bus. This result conflicted with the results obtained in this study which showed a much higher count for the bus (74,332) compared to the car (56,123). However; another study which examined UFP exposures on different modes of transport agreed well with the present study (Kaur et al., 2005b); it found that the highest average ultrafine particle count exposure was recorded on the bus (101, 364). As with the other pollutants, it could be argued that the frequent opening and the closing of the door, the open windows and the stop- and- go motion of the buses greatly increased the number of ultrafine particles entering the interior of the bus. Additionally, the build up of buses at the City Exchange bus stop would also have significantly added to the ultrafine count inside buses. While comparing the exposure on cycles to other modes of transport, previous research has consistently found that exposure of UFPs to cyclists are much lower than for car users (Kaur et al., 2005b; Boogard et al., 2009; Kaur and Nieuwenhuijsen, 2009). Gee and Raper (1999) suggested that the difference between the two modes could have resulted from varying proximity to the sources. Since the cyclist are able to dodge between vehicles, and keep close to the kerb, they are more able to avoid the direct path of emission. Furthermore, several studies showed a decrease in particle concentration with distance from the road, up to about 300 meters (Morawska et al., 1999; Shi et al., 1999, Hitchins et al., 2000). This also explains the much lower UFP count for the off- road cyclist (22,721), who was approximately three meters further away from the road and traffic, compared to the on- road cyclist (38, 897).

7.1.3 Variations within Studies

The scientific literature shows that there is a large variation of traffic exposures. These variations between and within studies could be explained by several factors. These include monitoring methods, averaging periods, local meteorological conditions, road configuration and intensity, type of vehicle, ventilation and driving behaviors, and proximity to preceding vehicles (Boogaard et al., 2009).

7.2 Elevated Exposures in Micro-environments: Inter-Segment Comparison

Past research has demonstrated that localised concentrations of air toxics can occur due to large or small emission sources, which can result in a “hot spot” of air pollution where the average concentrations of air pollutants are higher than those in surrounding areas (Zhu et al., 2008; Sweet and Vermette; 1992). Although there have been numerous studies conducted to measure personal pollution exposure levels on different transport modes (Dennekamp et al., 2002; Levy et al., 2002; Gulliver and Briggs; 2004; McCreanor et al., 2005), little scientific research has been conducted to investigate pollution level variations within a journey that might lead to commuters being exposed to short-term peak levels of pollutants while commuting. Past research has shown that although people might spend a fraction of their total journeys in micro-environments like bus stops, car parks and metro stations, they might be exposed to very high levels of pollutants in a very short period of time (Chau et al., 2000; Adams et al., 2001, Park et al., 2008). It is essential to understand the nature of such short-term elevated exposures to pollutants in micro-environments since it has been suggested that short-term peak exposures can have a significant effects on human health (Michaels, 1996; Michaels and Kleinman, 2000).

This section will discuss the pollution exposure levels experienced in Christchurch and Auckland at the indoor and outdoor bus stops, the sheltered and underground car parks, the out door train station and finally the indoor metro station.

7.2.1 Outdoor Bus Stop: Christchurch and Auckland

The out door bus stops in Christchurch were located at the centre of the city in front of the City Bus Exchange and at the University of Canterbury. Because of the high level of bus patronage at these locations, the frequency of buses arriving and departing was relatively high. In Auckland, on the other hand, the out door bus stop was located away from other bus stops, thus reducing the number of buses conglomerating at any one time. The time span between bus arrivals was also longer than it was for Christchurch. The discussion will only include comparisons between the bus stop, actual trip and waiting period at the centre of town exposures for Christchurch. For Auckland, only comparisons between the bus stop and actual trip exposures will be discussed.

In terms of CO exposure, the outdoor bus stop in Christchurch had the highest mean CO level compared to the journeys down Riccarton and Main North Road (Figure 4.3). This is especially important since the time spent waiting for the bus was under six minutes, while the two journeys took over 18 minutes to complete. The unusually high CO level could be attributed to the urban street canyons- tall buildings and narrow streets that trap pollution at the ground level (Israel, 2009). In addition, because the bus stops were located in areas where bus patronage was likely to be high (City Bus Exchange and

University of Canterbury), there would have been a high number of buses servicing the bus stops quite frequently. This build up of buses could have greatly increased the CO levels in a relatively short period of time. In Auckland, the exposure level for CO was lower at the bus stop compared to the actual bus trip. One explanation for this is that the bus stop was located away from a bus station, and was fairly isolated compared to the bus stops in Christchurch, thus a build up of several buses emitting CO into the surrounding area would have been unlikely.

While comparing particulate pollution across the segments, it is important to note the waiting period at the centre of town in Christchurch (W2) had unusually high levels of PM_{10} and $PM_{2.5}$. Such high levels of particulate matter can be explained by the presence of a construction site close to where the commuters waited. Since the waiting area (W2) was a vehicle-free zone, it can be concluded that the construction work was a major source of PM_{10}. Although the mean exposure for PM_{10} was lower at the bus stop compared to the journeys, it is important to realise that the maximum value experienced in that micro-environment (276 μg^3) far exceeded the maximum values on either of the journeys (29.88 μg^3 for J1 and 20.77 μg^3 for J2). Since the time spent at the bus stop was relatively short, it can be hypothesised that extreme values of PM_{10} were reached in a very short span of time. In Auckland, the highest mean $PM_{10,}$ $PM_{2.5}$ and PM_1 exposure levels were experienced at the outdoor bus stop compared to all other segments. One reason for this could be that the bus commuter was potentially exposed to PM particles emitted from vehicles passing by when they were waiting at the road-side bus stop (Tsai et al., 2008). Another possible explanation for higher mean exposures for all three grades of particulates is that the buses in Auckland could have been badly tuned, thus increasing its particulate emissions. Badly tuned vehicles contribute significantly to air pollution, and a diesel engine can continue running in a more neglected state than can a petrol engine (Ministry for the Environment, 2007). The movement in dust from the road resulting from the approaching bus could have also contributed to the PM_{10} exposure. With regards to $PM_{2.5}$ and PM_1 exposures in Christchurch, the outdoor bus stop had lower average levels (20.78 μg^3 and 11.02 μg^3 respectively) compared to the journeys (25.30 μg^3 and 15. 67 μg^3 respectively for J1, and 22.27 μg^3 and 12.44 μg^3 respectively for J2).

The higher mean exposures in the bus trips could be attributed to the fact that the in-vehicle pollution inside the bus from $PM_{2.5}$ and PM_1 was influential to average exposure. The frequent passenger movement inside the bus could have re-suspended dust and other particulates to increase the in-vehicle particulate levels. Furthermore, the open windows and the recurring opening and closing of doors could have allowed particulates to enter the bus compartment. The average UFP count (43,997) in the outdoor bus stop in Christchurch was lower than those in both bus trips (60,511 and 116,380 for J1 and J2 respectively). The higher averages during the journey could have resulted from increased in-vehicle contamination from emissions originating from surrounding traffic. Also, as the distance from the road is also a factor which influences UFP exposure (Morawska et al., 1999; Shi et al., 1999, Hitchins et al., 2000), the distance between the bus stop and the road could have effectively lowered emissions experienced at the bus stop.

As mentioned before, pollution exposure can vary within a few seconds and over a few meters as people move through polluted micro- environments. This implies that the influence of time- activity and movement can be easily missed by using averaged results, thus leading to an underestimation of exposures (Morowska et al., 2008). Shorter averaged periods [single journeys instead of the entire experiment run] showed that in some journeys, the mean pollution level at the outdoor bus stop exceeded those measured during the bus trip. This included all the pollutants monitored and was true for both Christchurch and Auckland (Chapter five, Section 5.3.1, Figures 5.21- 5.20; Chapter six, Section 6.3.1, Figures 6.17- 6.20). These show that pollutant levels can reach extremely high values in a very short period of time. Such high exposures in a short time can contribute to a lot to the total exposure of a commuter, and has major implications for any health effects.

7.2.2 Indoor Bus Stop

The indoor bus stop was situated inside the Christchurch City Bus Exchange in the Christchurch Central Business District. The mean CO exposure inside bus stop (2.55 ppm) was lower compared to the outside bus stop and both bus trips. This could have occurred because private vehicles, which are mostly run on petrol are not allowed to drive or park close to the indoor bus. However, a lot of bus traffic occurs in close proximity of the indoor bus stop. Most of the PM emissions are attributed to diesel fueled vehicles, while CO mostly originates from petrol emissions (Bergmans et al., 2008). This also explains why average PM_{10} level in the indoor bus stop was higher (43.90 ppm) than the mean levels found on J2 (Riccarton Road) and in the outdoor bus stop, even though less than four minutes were spent in the indoor bus stop. This agrees with past research carried out in West Yorkshire, England (Kingham et al.,1999 which showed highly elevated levels of particulate matter when entering an indoor bus station. This could be attributed to the fact that the bus stop was a confined space, which allowed contaminated air to accumulate and pollutant concentrations to increase. Poor ventilation could have also lead to higher particulate levels. Similarly for PM_1, the mean concentrations were higher in the indoor bus stop compared to J2 and the outdoor bus stop. Again, poor ventilation could be attributed to the higher mean exposures. However, for $PM_{2.5}$ levels, the indoor bus stop was seen to be less polluting than the actual bus trips and the outdoor bus stop. One possible explanation for this could be the higher exposures to the particulate during the journeys which had higher mean exposures due to the proximity of surrounding traffic. Despite lower average mean pollution exposures for CO and $PM_{2.5}$ for the overall journey over the entire experiment, while looking at single journey exposure, the mean level for all CO, PM_{10}, $PM_{2.5}$ and PM_1 were higher than those for the journeys. It is thus important to reiterate that using averaged results can easily lead to an underestimation of exposures influenced by time-activity and movement in certain micro-environments.

7.2.3 Car Parks: Sheltered and Underground

The sheltered car park in Christchurch was situated at the centre of town. Since it was a public car park, there was increased traffic leaving and entering the car park, especially at peak times. The underground car park in Auckland, on the other hand, was not accessible to the general public, but serviced businesses and organisations in the area. While the time spent in the Christchurch car park averaged less than four minutes, just over five minutes were spent in the Auckland one. Both periods of time were considerably shorter than the time spent on the actual car drive (average time spent on the Christchurch car rides totaled 17.52 minutes, and on the Auckland car journeys average time spent was 38.10 minutes).

The mean CO exposure in the car park in Christchurch averaged more in the car park than the journeys. The maximum level in the car park was highest compared to other segments (54.74 ppm). This is congruent to results in other studies obtained in CO exposure studies done in car parks. Papakonstantinou et al., (2002, pp. 933) reported that ' the garage micro-environment [is an] important determinant to CO exposure'. Similarly an earlier study (Barker and Fox, 1976) noted that instantaneous concentrations of up to 210 ppm were experienced in the exit area of a multi- storey car park, where traffic flows were restricted. The elevated levels of CO in the car park could be attributed to malfunctioning or insufficient ventilation which leads to a build- up of contaminated air. Comparing these results to the underground car park in Auckland, it was found that mean exposures in the car park were slightly lower than those found on the car journey. One reason for this could be that the traffic volumes in Auckland were much higher than they were for Christchurch, so the car driver was exposed to higher concentration while traveling in the car. Another potential explanation could be that while the Christchurch car park was a commercial car park open the public, the Auckland car park was only open to business employees. This would have reduced vehicle movement quite substantially in the underground car park due to reduced traffic flow. The car park could also have been better ventilated which allowed adequate mixing of inlet air with the indoor air, thus obtaining a uniform fresh air distribution (Papakonstantinou et al., 2002).

While examining particulate pollution in the car parks, the results showed that the average levels of all three fractions of particulate monitored exceeded the mean exposures experienced while traveling in the car. The maximum value for PM_{10} at the car park (100 μg^3) exceeded the maximum values found on both trips (62.70 μg^3 for J1; 94.80 μg^3 for J2). Since the car park got relatively busy during peak hours, there would have been a build up of slow- moving traffic either entering or exiting the car park.

Furthermore, all cars had to stop before entering and leaving the park to pay at the parking kiosk, and although the windows were kept shut for the entirety of the journey, the driver had to open the window to collect the ticket at the beginning and pay before leaving. This would have allowed the emissions from surrounding vehicles to enter the car, and contaminate the in-vehicle air, thus increasing the PM exposure. In Auckland, the results for PM exposures were slightly different. While the PM_{10} reached the highest mean exposure levels, the $PM_{2.5}$ and PM_1 levels were lower compared to the in-vehicle journey exposures. This could be potentially explained by the fact that the PM_{10} particulates did not originate from traffic sources, but were other suspended particles such as dust from the floor. The mean $PM_{2.5}$ and the PM_1 particulate exposures were higher for the car trips compared to the mean exposures at the underground car park. The journey exposures for all three grades of particulates reached maximum levels (shown as outliers in Figures 6.14, 6.15 and 6.16). The low levels in the car park could mean that the indoor air was not heavily contaminated by vehicle emissions. Adequate ventilation and low traffic movement could have both contributed to low vehicle emissions in the car park. Although the mean UFP count in the car park was lower in the Christchurch car park compared to the exposures in the car journeys, extremely high numbers were experienced in the micro-environment (Figure 5.20). This could have resulted from emissions from surrounding cars using the car park, especially when the windows were opened to receive and pay for the parking ticket. The slow moving and idling traffic could have also lead to the raised UFP levels in the sheltered car park.

As with other pollutants in other micro-environments, elevated levels were found in both the sheltered and underground car parks for all five pollutants monitored. This shows that while in some cases, the mean exposures may be lower in those micro-environments, pollutant levels can often reach very elevated levels.

7.2.4 Outdoor Train Station and Underground Metro Station

The results indicate that mean CO levels measured at the outdoor train station exceeded mean levels observed inside trains during the journey and at the underground metro station. While very little research has been done assessing CO comparisons between train platforms and inside trains, few studies have been carried out which measured PM exposures. While one study demonstrated that PM levels inside trains were significantly higher than on outdoor platforms (Park and Ha, 2008), another indicated the opposite, reporting higher PM values on the platform (Ripanucci et al., 2006). The reason for lower PM levels inside trains could be attributed to ventilation systems of the subway system filtering out coarse particulates. The elevated CO levels on the Auckland train platform could have occurred because of passengers smoking on the platform while waiting for the train. The significantly lower mean CO exposures inside Britomart, the underground metro station could have resulted from the fact that the metro station was well ventilated, which protected the interior from air pollution. Because the metro station was inaugurated six years ago, it is very likely that it has so far been well maintained.

7.2.5 Health Effects of Elevated Exposures

Though only a short time was spent in the built micro-enviroments mentioned in Sections 7.2.1-7.2.4, the commuters were exposed to very high elevations of the monitored pollutants. Such intense exposures of short durations should be of special concern since 'they produce an elevated dose rate which at target tissues and organs, potentially altering metabolism, overloading protective and repair mechanisms and amplifying tissue responses' (Preller et al., 2004, p. 643). Additionally, these large peaks of exposure may be especially harmful for sensitive individuals, like asthmatics, since these might significantly increase acute health risks (Briggs et al., 2008).

7.3 Other Factors

It has been established that the mode of transport commuters choose to travel by, and the type of transport micro-environment they spend their journey in both have a significant affect on their pollution exposure levels. Previous scientific studies on pollution exposure levels have found other factors to be influential on pollutant levels experienced by travelers while commuting in transport micro-environments. The two that were investigated in this research were the effect of wind speed and the time of day on commuter pollutant exposure levels.

7.3.1 Meteorological Factor: Wind Speed

Amongst all the meteorological variables, wind speed has been studied the most with regards to pollution exposure since it influences the dilution and dispersion of pollutants (Kaur et al., 2007). Numerous studies have demonstrated that an increase in wind speed leads to a reduction in exposure concentrations (Bevan et al., 1991; Kingham et al., 1998; Krausse and Mardaljevic, 2005). For example, Gomez Peralez et al., (2004) found that in-vehicle $PM_{2.5}$ and CO reduced by 24% and 12% respectively for every 1 m/s increase in wind speed in minibuses and buses. Similarly, Koushki et al., (1992) reported that an increase in wind speed from 2 m/s to 20m/s lead to a 27% decrease in in- vehicle CO exposure concentrations in Saudi Arabia. Other ambient studies have reported lower UFP count concentrations at lower wind speeds (Molnar et al., 2002; Holmes et al., 2005). The results from this research reflect the trends presented in past scientific studies. Wind speed was a significant determinant of pollution exposure for all pollutants monitored in both Auckland and Christchurch (Table 5.46 and 6.40). This could be explained by the fact that higher wind speed affects the rate of transport of particles and pollutants and also increases the rate of dilution with cleaner air

7.3.2 Time of Day

The effect the time of day has on personal pollution exposure levels has not been as thoroughly studied as the effect of wind speed on exposures. One study conducted in Mexico City (Gomez- Perales at el., (2007) found that concentrations for PM , CO, and benzene were all higher in the morning than in the afternoon rush hours minibuses, buses and metro. Similar results were derived in this study: pollution exposure levels were statistically significantly higher in the mornings compared to the afternoons for all pollutants monitored and across all modes (Table 5.48 and 6.42). This could be related to the fact that morning rush hours were less windy than the evening rush hours during the study period in both Christchurch and Auckland. In Christchurch, 63% of the mornings just 31% of the afternoons had low wind speed. Similarly, in Auckland, 93% of the mornings and just 23% of the afternoons had low wind speed. This could have been caused by an inversion layer in the cities: the morning low- wind speed creates all the conditions to increase air pollution concentrations at ambient level (Jauregui et al., 1973; Riveros et al., 1998). The inversion layer remains during the morning rush hour, but dissipates by the afternoon rush hour (Gomez- Perales te al., 2007). The resulting high wind speed could have contributed to the dispersion of pollutants, thus decreasing exposure concentrations. In addition to this, higher traffic numbers can be expected in the mornings because of commutes to work and school at morning peak times. However, in the afternoons, because school closes approximately around 3PM, there might be lower traffic volumes.

7.4 Limitations

A number of limitations were identified in this study. Their potential contributions to the research outcomes are discussed in this final section.

One of the most significant limitations of this research study was equipment failure. One of the GRIMM Dust Monitors, which simultaneously measured all three fractions of particulates, malfunctioned during the length of the study period in Auckland. Since this GRIMM was used on the train journey, no PM data could be gather for that particular mode of transport. In addition to this, corrections could not be applied to the Auckland data gathered from the TSI 3007, therefore there is a lack of UFP data from the Auckland monitoring sites. The TSI 3007 also proved to be very sensitive to movement, displaying 'tilt errors' if the equipment kit experienced sudden jolts. The machine required re-starting after these 'tilt errors'. Although all measures were taken to ensure the stability of the machine inside the kit, it was not entirely possible to avoid the 'tilt errors' especially on the cycles, which lead to some loss of UFP data in Christchurch.

This exposure study was carried out for a little over three weeks in Christchurch and Auckland. Five different pollutants were monitored across five modes in two study sites, which resulted in a voluminous set of data. Working on such a large data set could have potentially lead to mistakes during data entry. Such mistakes; however, are expected to be minor.

The wind data for the experiment were gathered from stationary sites in Christchurch and Auckland located away from the monitoring sites. The averages from the stationary sites might have been a poor reflection of the wind speed at the study site since wind speed can vary over distances. Several studies have reported that wind direction is also likely to be an important influence on dispersion patterns and exposures (Hitchens et al.,2000; Briggs et al., 2008); however, the affect of wind speed was not assessed in this study. Other meteorological factors such as humidity and temperature have also been reported to significantly affect personal exposure levels (Nieuwenhuijensen and Schenker, 1998; Vanwijnen et al., 1995). These factors; however, were not considered in this study.

Another limitation of this research project is that the monitoring was conducted during a brief period of summer so the results obtained are not representative of the winter conditions. Many studies have identified traffic counts to be a significant determinant ($p<0.05$) of pollutants, especially UFPs and CO exposure concentrations (Chan et al., 1991;Kaur, 2006); however, traffic counts along the study routes were not assessed in this study. Also, for the study design, only three routes were investigated thus covering only a small fraction of New Zealand.

CHAPTER EIGHT

Conclusion

8.0 Introduction

The research presented in this thesis was designed to assess the effect of traffic emissions on personal exposure. More specifically, this project intended to examine how exposures differed on different modes of transport and also to investigate the extent to which transport micro-environments such as car parks, bus stops and metro stations contributed to personal exposure levels. This study is the first of its type in New Zealand, which simultaneously monitored CO, PM and UFP concentrations in the transport micro-environment.

The objectives outlined in Section 1.3.2 have been addressed in the two result chapters (5-6), and the key outcomes are examined in Chapter 7. This chapter will present the overall conclusion of the study, and discuss policy implications and recommendations. In addition, areas of future research will also be identified.

8.1 Thesis Objective Revisited

As it has been shown in this research, vehicular traffic emissions are a significant source of air pollution in populated urban areas, especially in the transport micro-environment. This results of this study showed that the mode of transport is a significant determinant of personal exposure to pollutants. The information gathered indicated slightly different results for Christchurch and Auckland, possibly due to variations in back ground levels, traffic counts and/or meteorological conditions at the time of monitoring.

In terms of pollution exposures for the inter-modal comparison, the mode of transport was a significant determinant of personal pollution exposures. The CO exposure was highest for car users in both cities, most likely attributed to self-pollution or to emissions entering the car from surrounding traffic through the air vents. The bus in Christchurch had the highest levels of particulate exposure. High levels of PM contamination in the bus could have resulted from the constant stop-and-go movement of the bus which allowed particulate matter to enter the bus. Furthermore, because the bus was not air-conditioned, higher levels of the pollutant could have entered the bus through the open windows. High passenger movement inside buses could also be attributed to the increased levels of PM_{10} inside the bus, through the resuspension of coarse particles. The cyclists in Christchurch had the lowest levels of CO and UFPs, probably because the cyclists were further away from the traffic sources. The fact that the on-road cyclist rode along the cycle-path, and not directly through the traffic could have resulted in lower exposure levels. In contrast, since the cyclist in Auckland had to weave through the traffic due to a distinct lack of a cycle lane along most of the route the Auckland, he was exposed to direct emissions originating from the traffic on the road.

Another important finding that emerged from this research was that commuters can be exposed to highly elevated levels of pollutants in a relatively short span of time in micro-environments such as car parks, bus stops and metro stations. The mean exposures for some pollutants were significantly higher in some of these built micro-environments than any other part of the journey, including the actual commuting journey. Elevated levels of exposures, however, were present in all the micro-environments even though the commuters spent the shortest time at the car parks, bus stops and the metro station. These levels exceeded levels where health effects have been reported (Westerdahl et al., 2009).This is of special importance since commuters can be exposed to extremely high levels of pollutants in a very short period of time.

8.2 Implications for Health

Motor vehicles emit a range of air pollutants that are known to be associated with adverse health effects (Chertok et al., 2004). Numerous studies have shown that the air in transport micro-environments can be unsafe due to high concentrations of CO, suspended particles (PM and PM), volatile organic compounds (VOCs), amongst others (Kuo et al.,2000; Adams et al., 2001). More recently, scientific evidence has identified UFPs from traffic sources as a potential health threat to nearby population. Given their small size, UFPs have been shown to efficiently penetrate the respiratory system and even transfer to the extrapulmonary organs, including the central nervous system (Hagler et al., 2009). 'UFPs are linked to adverse effects on respiratory and cardiovascular health, with comparably stronger associations observed than for $PM_{2.5}$' (Hagler et al., 2009, p.1229). In New Zealand, nearly half of the total cases of premature death due to CO, PM_{10} and NO_2 can be attributed to air pollution from vehicles (Air Quality Report Card, 2009). There is an overwhelming economic cost of urban air pollution in New Zealand costing 1.14 billion dollars every year and 285,000 restricted activity days (Fisher, et al., 2007). The Ministry of Environment introduced national environmental standards in 2005 to provide a guaranteed level of protection of health, however most environmental guidelines are based on exposure estimates from fixed monitoring sites which significantly underestimate or have no association with population sub-groups (Chan and Wu, 1993). Furthermore, the NES do not include indoor air pollution, which has been proved to be closely linked to personal exposure. Although the mean exposure levels for the pollutants measured complied with these standards, maximum values for all pollutants across all modes significantly exceeded the highest threshold. This was especially evident in the specific micro-environments, including both the indoor and outdoor bus stops, the sheltered and underground car parks, and the outdoor train station (Chapters 5-6) where the commuters spent a very short duration of time. It is essential to realise that these short-term elevated exposures may be extremely important when examining health effects of pollutants as several studies have documented that adverse health effects associated with air pollution may be attributable to short-term (a few minutes) exposure (Quintana et al., 2001; Cairncross et al., 2007).

8.3 Policy Implications and Recommendations

The results presented here have relevance for both public health and for policies aimed at reducing human exposures to traffic-related air pollution.

Indoor air quality is closely linked to personal exposure, and its subsequent effect on health. As was evidenced by this research, pollutant levels inside buildings can often greatly exceed the national guidelines. This has implications on the safety of indoor micro-environments such as underground and sheltered car parks, indoor bus stops and metro stations. This highlights the need to ascertain safe indoor pollutant levels and replace NES guidelines with compulsory safety standards for both indoor and outdoor air.

Despite the toxicity of UFPs, which some studies report can be greater than other particulate matter (Wahlin et al., 2001; Elder et al., 2006) no health guidelines have been developed for the pollutant. Policies should be aimed at examining exposure-response relationships with regards to UFPs in order to quantify a threshold level for national regulations. Future control and management strategies should also target a decrease of these particles in urban environments.

In-vehicle pollution can occur due to outdated engine technology and poor maintenance of vehicles (Wohrnschimmel et al., 2008). Management alternatives for the mitigation of in-vehicle exposure should be introduced to reduce pollution levels in vehicles. Although vehicles in New Zealand are required to ensure that they are safe to drive on the road, perhaps more stringent measures could be adopted to guarantee proper maintenance of engine and exhaust pipe.

It is known that vehicle exhaust from diesel-vehicles is a major source of fine particulate matter in transport micro-environments (Chan et al., 2002). Cleaner fuel alternatives for public buses should be introduced to lower PM exposure levels inside buses. Management initiatives could encourage better bus designs which lower emissions entering the bus compartment. Research has also shown that buses that travel on designated bus lanes could potentially be exposed to lower levels of vehicle emissions (Wohrnschimmel et al., 2008). This could be attributed to the fact that the use of bus lanes protects bus commuters from surrounding traffic to some extent. Although there are a number of bus lanes in Christchurch and Auckland, other vehicles have been known to use them. Stricter laws should be enforced to ensure that such lanes are only used by buses.

This research showed that cyclists who were further away from road traffic were exposed to lower exposure levels of traffic emissions. Policies should be aimed at introducing cycle lanes, especially in areas where traffic volumes are high. Policies should be directed at increasing separation of road vehicles and cyclists by designing and constructing dedicated, quiet and convenient cycling routes. Not only would this protect cyclists from vehicle emissions, it would also encourage environment-friendly forms of transport which promote sustainability.

Results from this research also showed that built transport micro-environments could experience extremely high levels of pollutant exposures. Although commuters spend a relatively short time in such environments, such short-term peak exposures could contribute significantly to adverse health effects. It is thus imperative to incorporate policies which ensure that such built environments are as safe as possible in terms of keeping exposure levels at a minimum. This could include regulation requiring proper ventilation inside buildings, which could significantly reduce the penetration of outdoor air pollutant concentrations into buildings. The design of an efficient ventilation system will result in a better quality of air inside buildings (Papakonstantinou et al., 2003). Future initiatives could be taken to build bus stops and stations further away from road traffic, which could lead to lower exposure levels in those places.

Future policies should also target initiatives to make information readily available and more accessible to commuters and the general population so measures and behaviours can be adopted to reduce exposure levels and potential adverse health affects. This could encourage people to avoid certain activities, such as lingering at car parks or bus stops, which could significantly increase personal exposures. Commuters could also choose to travel at times when traffic volumes are low or stay indoors in calm conditions to help reduce their personal exposure.

Urban designers and city planners could use these findings to design cities which are effective in reducing personal exposure levels. For example, they could design cities which allow more airflow through the city to cut down pollution levels.

8.5 Future Research

A number of avenues have been identified that require further investigation which woud increase the level of understanding of personal exposure and consequent health effects of traffic emissions in a variety of transport micro-environments. Further research would also assist in developing targeted control strategies in urban air quality management and to better understand health risks posed by air pollutants in different conditions.

Due to equipment failure, no PM data could be gathered for the metro station or inside trains in Auckland. Previous research has identified high levels of particulate matter in metro stations, which may originate from outside or be generated internally (Sitzmann et al., 1999; Gomez-Perales et al., 2004;). No previous studies have been carried out in New Zealand to measure pollution levels in Britomart, the underground metro station. Such research would be of special significance since Britomart is designed to serve 10,500 passengers during the peak hour, and rail patronage has increased from 2.5 million journeys in 2003 to 5.7 million in the year ending 2007. This alludes to the fact that millions of commuters who use the underground station may be exposed to high levels of particulate pollution.

UFPs are of interest as a potential health threat to commuters in the transport micro-environment. Again, due to equipment failure, no UFP data could be gathered in Auckland. Future research could be dedicating to assessing UFP levels on different modes of transport, and in different built micro-environments.

Pedestrian exposure was not measured in this research. Only a few experiments have studied pollution exposures while walking (Adams et al., 2001; Dennekemp et al., 2001). The results from one study (Briggs et al., 2008) have shown than mean exposures while walking are greatly in access of those while driving for particulates. These findings suggest that care is needed while implementing policies which encourage walking instead of driving. More research is required to confirm the effects of exposures of changes in travel modes.

Studies done in the past have shown that cyclists are exposed to lower levels of pollutants compared to car drivers (Boogard et al., 2009). However, total pollutant dose is likely higher for cyclists than for car drivers since cyclists inhale more pollutants due to an increased breathing rate. For example, McNabola et al., (2008) reported that the calculated overall relative absorption rates could be as high as 38% for cyclists compared to car drivers. The dosage rate was not taken into account for this research project. Future scientific studies need to assess the influence of breathing rates and doses of pollutants inhaled in order to accurately measure personal exposure levels on when travelling by cycles.

Previous research carried out has identified traffic counts to be a significant determinant ($p<0.05$) of exposure concentrations for CO and UFPs (Kaur, 2006). This study did not take traffic counts into account when assessing exposure levels for commuters. Since traffic is the main source of pollutants in the transport micro-environment, future research in New Zealand should investigate the influence traffic numbers have on commuters' exposures to pollutants.

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